BIODEGRADABLE PLASTIC MULCH AND SUITABILITY FOR SUSTAINABLE AND ORGANIC AGRICULTURE

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Biodegradable Plastic Mulch and Suitability for Sustainable and Organic Agriculture

Biodegradable plastic mulch (abbreviated as plastic BDM hereafter) offers crop production benefits similar to polyethylene (PE) mulch but is designed to be tilled into the soil after use thereby eliminating waste and disposal challenges. This publication explains the use of plastic mulch in agriculture, what plastic BDMs are made from, and what constitutes biodegradability. It also provides information about the suitability of plastic BDM for organic agriculture. A **glossary** of terms associated with the topic is included at the end of this publication.

The use of plastic mulch in agriculture

PE mulch is used for crop production worldwide because it helps to control weeds, conserve soil moisture, increase soil temperature, and increase crop yield and crop quality compared to growing plants on bare ground (Kasirajan and Ngouajio 2012). PE mulch is also readily available at a relatively low cost (Ghimire and Miles 2016). Despite these benefits, the sustainability of crop production using PE mulch has been called into question since PE mulch is not biodegradable and not readily recyclable. Many plastic recyclers will not accept PE mulch because it is contaminated with soil and crop debris (up to 50% by weight) after use (Kasirajan and Ngouajio 2012). Further, there are few plastic mulch recycling facilities in the U.S., so less than 10% of PE mulch is currently recycled (Miles et al. 2017).

The projected use of plastic mulch in North America is estimated to be about 117,700 tons in 2017; most used mulch will be disposed in landfills, stockpiled, or burned on farms (Figure 1) (MarketsandMarkets 2012). The disposal of PE mulch raises many concerns. **Degradation** of PE mulch in landfills is negligible (complete decomposition will take more than 300 years in soil) and potentially forms environmentally harmful chemical byproducts, such as **aldehydes** and **ketones** (Hakkarainen and Albertsson 2004; Ohtake et al. 1998). PE mulch disposal (not including labor) can cost up to $236 per acre (Galinato et al. 2012; Galinato and Walters 2012). In addition, 5–10% of PE mulch can remain in the field when the mulch is removed from beds (Lluís Martín-Closas, unpublished data). On-farm burning of PE mulch can release the airborne pollutant **1,4-dioxane**, among other undesirable environmental impacts (Levitan 2005).

In some areas (e.g., China and southern Spain), farmers have been incorporating PE mulch into soil annually, and PE mulch accumulation in field soil is so significant that soil water retention and crop yield are reduced (Liu et al. 2014; Steinmetz et al. 2016). PE mulch fragments from such fields are dispersed into the environment by wind and water erosion, thereby causing further pollution.

Figure 1. Typical post-season PE mulch waste ready for transport to the landfill. (Photo by C. Miles)

Plastic BDMs offer a potential solution to disposal and environmental issues associated with PE mulch use. To be a viable alternative, plastic BDMs must perform comparably to PE mulch for crop production, especially in terms of durability and weed control (Figure 2). Several studies have shown that plastic BDMs can perform comparably to PE mulch in annual vegetable cropping systems (Cowan et al. 2014; Ghimire et al. 2018; Li et al. 2014a; Miles et al. 2012; Wortman et al. 2016). Further, after plastic BDM is incorporated into the soil at the end of the cropping season, it should rapidly degrade without negatively affecting soil health. Investigations to date have revealed that degradation is a function of environment, and short-term effects on soil quality indices may be minor (Brodhagen et al. 2015; Li et al. 2014a; Li et al. 2014b). However, protracted use of plastic BDMs on soil health is not fully understood or comprehensive; long term investigations are needed (Brodhagen et al. 2017).

Figure 2. Starch-based plastic BDM (BioAgri) at WSU Northwestern Washington Research and Extension Center at Mount Vernon, WA prior to harvest (*left*), one year later on the soil surface (*center*), and nine months post incorporation (*right*). [Photos by J. Cowan (*left*) and C. Miles (*center and right*)]

What constitutes "biodegradability"?

The term "biodegradable" is often a misused and misunderstood term, especially when used to describe plastic. Much of this confusion is because it is first necessary to define the environment where biodegradability occurs, as oxygen, temperature, and moisture levels will all affect the extent of biodegradation as well as its rate (how long it takes for biodegradation to occur). For example, a plastic may be biodegradable under one environment (such as **composting**) but not another (field soil for example). Therefore, when stating that a plastic is biodegradable, it is also necessary to state the environment under which it is biodegradable. For example, the ASTM International (formerly known as the American Society for Testing and Materials) standard D6400, and a similar standard issued by the International Organization for Standardization, ISO 17088, specify criteria for the biodegradability of plastics under industrial composting conditions based on standardized laboratory tests (ASTM International 2012a). ASTM D6400 utilizes ASTM D5338, a standardized test that measures the aerobic biodegradation of plastic materials under controlled composting conditions. The ASTM D6400 standard specifies that 90% of carbon atoms must be **mineralized** in 180 days to carbon dioxide and water. **The ability of a BDM to meet the composting standard is considered the first critical test of biodegradability; if a mulch is not compostable, it will likely not biodegrade under field conditions.** Thus, farmers and others using or recommending plastic BDMs should first check to see if the product has been tested according to the ASTM or ISO composting standard and meets the biodegradability criteria. If the product has not been tested, then it should be assumed the mulch is not biodegradable.

There is also a standardized test method for measuring biodegradation of plastic in soil, ASTM D5988 or ISO 17556 (ASTM International 2012b). These methods are laboratory tests, not standards, so they do not specify biodegradation criteria to be achieved. Moreover, currently no standard exists for assessing the biodegradability of plastics buried in soil under diverse field conditions, although ISO and ASTM International are each developing a soil biodegradation standard. In the proposed standards, 90% of a plastic BDM must break down into carbon dioxide and water, and the remaining 10% into environmentally benign substances including **microbial biomass** within one to two years.

How plastic BDMs are made

Knowing the ingredients of plastic BDMs, along with information about how they are made, will expand the general understanding of BDMs. Plastic BDM is made from feedstocks (raw materials) that are either **biobased**, derived from fossil fuels, or a blend of the two (Table 1). (Additives such as **plasticizers** and **fillers** are discussed below.) Biobased **polymers** can be divided into three categories: (1) extracted directly from natural materials, such as plants, e.g., starch and **cellulose**; (2) produced by **chemical synthesis** from **biologically-derived monomers**, such as synthetic **polymerization** of lactic acid into polylactic acid (PLA); and (3) produced by microorganisms, such as polyhydroxyalkanoates (PHA) (Jamshidian et al. 2010). Polymers such as PLA or PHA have deficiencies in mechanical properties compared to PE but blending improves the mechanical properties. For instance, PLA by itself is very brittle, but when it is blended with PHA or polybutylene adipate terephthalate (PBAT), the brittleness is reduced. The most common biobased feedstocks used to make plastic BDMs are starch, PLA, and PHA. This information is of particular importance for organic agriculture as the USDA National Organic Program (NOP) has rules that BDMs must meet to be allowed in certified organic production (see section on Organic Agriculture below).

It is also worth noting that the percent biobased content is not necessarily an indicator of biodegradation under field conditions since some biobased ingredients such as PLA (polylactic acid) require higher temperature for biodegradation (Figure 3).

Table 1. Trade names of plastic BDMs, their primary constituents, and their polymeric feedstocks; constituents can change over time as technology changes. (Adapted from Miles et al. 2017).

Trade name	Polymer/Polymer Blend[z]
Bio360	Mater-Bi (Starch) + PBAT
BioAgri	Mater-Bi (Starch) + PBAT
Biocycle	Sucrose/PHA blend
Bio-Flex	PLA/co-polyester
Biomax TPS	Starch + TPS
Biomer L	PHA
Biopar	Starch co-polyester
Biosafe	PBAT/Starch blend; PBS; PBSA
ecoflex	PBAT
ecovio	PLA + PBAT
Envio	PBAT + PLA + starch blend
GreenBio	PHA
Ingeo	Starch + PLA; PBS + PLA
Mater Bi	Starch blend
Naturecycle	Starch
Paragon	Starch + TPS
ReNew	PHA

[z] Abbreviations: PBAT — polybutylene adipate terephthalate; PBS — polybutylene succinate; PBSA — PBS-co-adipic acid; PHA — polyhydroxyalkanoate; PLA — polylactic acid; TPS — thermoplastic starch.

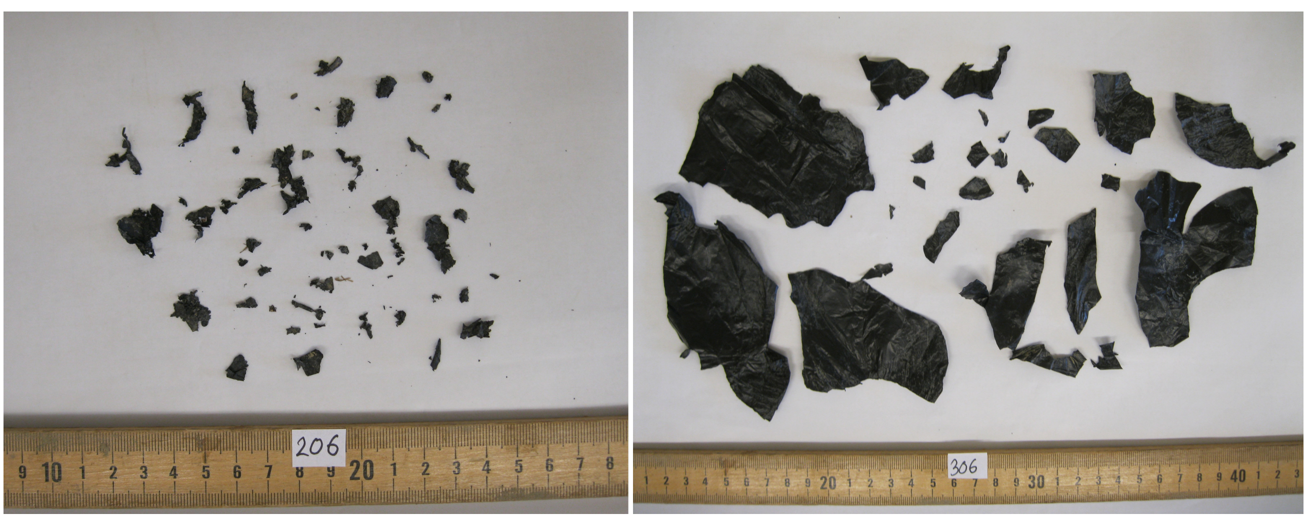

Figure 3. Samples of plastic BDM Naturecycle, approx. 20% biobased (*left*), and an experimental polylactic acid (PLA)/polyhydroxyalkanoates (PHA) mulch, 86% biobased (*right*), recovered six months after soil incorporation in the field at Mount Vernon, WA (ruler units are cm). (Photos by S. Ghimire)

Starch is a natural **polysaccharide** composed of straight-chain amylose and short-chain, branched amylopectin. Starch used in biodegradable plastics is frequently derived from corn, sugar beet, switchgrass, or sugar cane. High-amylose starch is processed into **thermoplastic** starch (TPS) by **extrusion** with water and alcohols (usually glycerol, a biobased co-product from biodiesel manufacturing) at relatively high temperatures. **Starch sourced in the U.S. may be derived from genetically modified (GM) crops, specifically corn or sugar beets, which is not permitted in organic agriculture as genetically modified organisms (GMOs) are an excluded method.**

To improve the functional and processing properties of the plastic, plasticizers are added. The primary plasticizers added to TPS are alcohols (principally glycerol), polyoxyalkenes, and other surfactants (Shanks and Kong 2012). **TPS costs less than other starch feedstocks and now it is the most common biobased feedstock used in plastic BDMs** (Miles et al. 2017)**.**

PLA is a thermoplastic **polyester** derived from renewable resources, such as corn 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 to other biobased biopolymers (Hayes et al. 2012; Jamshidian et al. 2010).

PHA is a class of polyesters created by a natural, one-step bacterial **fermentation** of plant sugars and lipids. Over 90 genera of bacteria can produce PHA (Kim et al. 2007). Poly(hydroxybutyrate) (PHB) and poly(hydroxyvalerate) (PHV) are the two most important commercial PHAs. PHA **copolymers** or copolymer-starch blends tend to degrade more rapidly than PLA-based products, making them more suitable for single-season BDM (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 and PHA can be produced without using GMOs during the fermentation process, **most commercially available PLA and PHA are produced through fermentation using GM yeast and bacteria for increased productivity** (Khemani and Scholz 2012; Reemmer 2009; USDA 2012)**.**

The most common fossil fuel-based polymers used to make plastic BDM are poly(butylene-adipate-*co*-terephthalate) (PBAT), poly(butylene succinate) (PBS), and poly(butylene succinate adipate) (PBSA). PBAT is fully biodegradable under composting conditions and has high elasticity, wear, and fracture resistance, as well as resistance to water and oil. PBS is a thermoplastic polyester with physicochemical properties comparable to polypropylene. All of these **synthetic** polymers provide functionality, flexibility, and affordability to plastic films, and can be degraded by bacteria and fungi commonly found in soil (Mohan and Srivastava 2010; Eubeler et al. 2009; Kawai 1995; Swift 1993). As a result, these synthetic polymers serve as the major components of plastic BDMs.

Plastic BDM is manufactured using conventional technologies

Manufacturing plastic mulch involves the addition of plasticizers, fillers (e.g., $CaCO_3$), lubricants that enhance the flow of molten polymer through the processing machinery, **nucleating agents** to control mechanical properties, stabilizers that prevent polymer breakdown by ultraviolet (UV) light, and colorants/dyes (e.g., **carbon black** that may or may not be naturally derived). The additives used in commercial plastic BDMs may or may not be produced from GMOs; however, it is difficult to determine the identity and concentration of additives in any mulch product since this information is proprietary to a mulch manufacturer. **Currently, biobased mulches are not tested for the presence of GMOs since DNA may be degraded following fermentation and processing to the point where GMO status is not discernable using available broad-spectrum quantitative polymerase chain reaction (PCR) tests** (Miles et al. 2017).

Plastic BDM in organic agriculture

The USDA NOP added biodegradable biobased plastic mulch to the list of allowed synthetic substances for organic crop production in October 2014. According to the organic standard [7 Code of Federal Regulations, Section 205.601 (USDA 2014)] an acceptable BDM film must:

1. Fulfill criteria for being biobased as evaluated using standardized tests such as ASTM D6866.
2. Be produced without organisms or feedstock derived from excluded methods (e.g., GMOs) [7 CFR, Section 205.601(b)(2)(iii)].

3. Meet compostability specifications of either ASTM D6400, ASTM D6868, European Standards (EN) 13432, EN 14995, or ISO 17088 (7 CFR, Section 205.2).
4. Reach at least 90% biodegradation in the soil within two years or less as evaluated using standardized tests such as ISO 17556 or ASTM D5988.

No plastic BDM products have been approved for use in organic cropping systems in the U.S. because currently available products are not completely biobased (USDA 2015). Plastic BDM products currently available in the marketplace have a maximum 20% biobased content (OMRI 2015). While some products on the market claim to have higher biobased content, product manufacturers have not verified those claims using the standardized test (ASTM D6866). Moreover, the use of GMOs in plastic BDM feedstocks as well as in the mulch production process is prohibited (USDA 2013).

Testing soil biodegradability of plastic mulch

While there is no standard for testing biodegradability of plastic mulch in the field, most commercially available plastic BDMs have undergone basic biodegradation and compostability testing (fulfilling the laboratory tests described above). Growers and agricultural professionals should check a mulch product to see if it has been tested using these standardized tests. **If biodegradability test results are not included on the product label, then it should be assumed the product does not meet the standards.**

While there is uncertainty about how plastic mulches will biodegrade in soils under diverse field conditions, this area of research and development is receiving active attention (Ghimire et al. 2017). New findings and technical advances are likely to be forthcoming in the near future. Both ISO and ASTM are developing new soil biodegradation standards, and university research programs are testing the main plastic BDMs sold in the U.S. (Figure 4).

Washington State University and University of Tennessee-Knoxville are conducting a five-year study (2015–2019) funded by the USDA Specialty Crop Research Initiative to evaluate long term effects of plastic BDMs in a vegetable production system. This study includes: (1) yield and quality of vegetable crops (pumpkin, sweet corn, and green pepper) grown with plastic BDMs, (2) impact of repeated tillage on plastic BDM biodegradation and soil quality, (3) the presence of harmful residues, fragments, or by-products potentially remaining in the soil that could negatively impact soil and plant health in production systems, and (4) the economics of using plastic BDM. Results indicate that crop yield and quality are equal between plastic BDM and PE mulch, and soil and climate factors affect the rate of mulch degradation. These results emphasize the importance of testing a plastic BDM in the environment where it will be used. See www.biodegradablemulch.org for up-to-date information from this research project.

Figure 4. Laying a BDM (*left*) and pumpkin plants with plastic BDMs two weeks after transplanting (*right*) at WSU Northwestern Washington Research and Extension Center, Mount Vernon, WA. (Photos by S. Ghimire)

Prospects for plastic BDM in organic and sustainable agriculture

The price of biobased feedstock is generally three times higher than petrochemical feedstocks, and so there is low possibility of shifting from ≤20% biobased BDMs to completely biobased BDMs in the next 3–5 years as this would be unaffordable for farmers. Further, GM microbes are currently used in the fermentation of feedstocks to manufacture BDMs; GM microbes increase the fermentation efficiency and lower the cost of biobased plastic. It is important to note that using non-GM microbes would not increase the biodegradability of BDMs. Therefore, if the U.S. organic standard requiring 100% biobased content and non-GMOs in the manufacturing process of BDMs remains, it is unlikely that manufacturers will be able to provide new affordable BDMs that meet these organic standards in the next 3–5 years.

While the use of non-biobased feedstocks and GMOs prohibit the use of plastic BDMs in organic production systems in the U.S., environmental and economic sustainability are promoted when plastic BDMs are completely biodegradable and affordable. Since plastic biodegradation is not based on the amount of biobased content (Figure 3), it is important to focus on the *biodegradation* of mulch in field environments and the *fate* of the resulting molecules, rather than on the *source* of the carbon in a biodegradable polymer. For example, fossil fuel polymers can be used as feedstocks to make many biodegradable materials. Likewise, the use of GMOs in the fermentation process of biobased feedstocks can reduce the overall cost of plastic BDM production, and can contribute to the economic sustainability of using plastic BDM. Thus, a mulch that is completely biodegradable regardless of the source of feedstock could become a sustainable alternative to PE mulch by reducing global agricultural plastic waste and contributing toward agricultural productivity, while preserving soil health and overall environmental quality.

Glossary

(Adapted from Corbin et al. 2013; Miles et al. 2015)

1,4-dioxane. Heterocyclic organic compound containing two ether (-O-) linkages, is poorly biodegradable and is a potential contaminant in ground water.

aldehyde. Organic compound in which a carbonyl group, a functional group composed of a carbon atom double-bonded to an oxygen atom, is bonded to one hydrogen atom and to one alkyl group or side chain.

biobased. Biobased feedstocks are obtained from renewable resources, that is, plant or animal mass derived from carbon dioxide recently fixed by photosynthesis.

biodegradable plastic. Degradable plastic in which the degradation results from the action of living organisms such as bacteria, fungi, and algae.

biologically-derived. Natural substances derived from living organisms such as cells, tissues, proteins, and DNA.

biosynthesis. Enzyme-catalyzed process where simple compounds are joined together or converted into other compounds in living organisms.

carbon black. Black color pigment, produced from coal tar, biomass, or vegetable oil.

cellulose. Polysaccharide consisting of a linear chain of glucose monomers. Cellulose is the main constituent of plant cell walls.

chemical synthesis. Purposeful execution of chemical reactions to obtain a product, or several products.

composting. A managed process in aerobic conditions of the biological decomposition of biodegradable materials into carbon dioxide, water, and stabilized organic matter called compost.

copolymer. Polymerization of two or more different monomers.

degradation (of plastic). Change in properties of a polymer-based product, such as mechanical strength, color, or shape, due to environmental factors, such as sunlight, heat, moisture, acids and bases, and microorganisms.

extrusion. A process by which a heated polymer is forced through an orifice or die to form a molten stream that is cooled to form a filament fiber, thin film, or a ribbon possessing specific geometric shape.

fermentation. The process in which cells (microorganisms, plant or animal cells) are cultured in a bioreactor in liquid or solid medium to convert organic substances into biomass (cell growth) or into particular products (polymers).

fillers. Particles added while manufacturing plastics to lower the consumption of more expensive materials or to improve properties of the material (e.g., calcium carbonate).

genetically modified organism (GMO). An organism whose genetic material has been altered using genetic engineering techniques; also referred to as a genetically engineered organism (GEO).

ketone. Organic compound in which a carbonyl group, a functional group composed of a carbon atom double-bonded to an oxygen atom, is bonded to two carbon atoms.

microbial biomass. The total mass of all microorganisms in a given area or volume (of soil).

mineralization. Microbial conversion of organic matter into inorganic substances, such as water and carbon dioxide.

monomer. Molecule that can react with other molecules to form very large molecules, or polymers.

nucleating agents. Insoluble particulate that increases the rate of crystallization when semi-crystalline polymers crystallize from the melt, typically during the cooling phase.

plasticizer. Additive that increases the plasticity or viscosity of a material.

polyester. Polymer that contains the ester functional group in their main chain. Polyesters include naturally occurring chemicals, such as the cutin of plant cuticles, as well as synthetics through step-growth polymerization such as polybutyrate, and frequently possess high biodegradability.

polymer. A molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass.

polymerase chain reaction (PCR) test. Technique to amplify a single copy or a few copies of a segment of DNA across several orders of magnitude, generating thousands to millions of copies of the DNA sequence.

polymerization. Any process in which relatively small molecules, called monomers, combine chemically to produce a very large chainlike or network molecule, called a polymer.

polysaccharide. Polymeric carbohydrate molecule composed of long chains of monosaccharide units bound together by glycosidic linkages**.**

synthetic material. A substance that is formulated or manufactured by a chemical process or by a procedure that chemically changes a substance extracted from naturally occurring plant, animal, or mineral sources.

thermoplastic. Polymer that becomes pliable or moldable above a specific temperature and solidifies upon cooling.

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References

ASTM International. 2012a. Standard specification for labeling of plastics designed to be aerobically composted in municipal or industrial facilities. ASTM D6400-12. ASTM International, West Conshohocken, PA.

ASTM International. 2012b. Standard test method for determining aerobic biodegradation of plastic materials in soil. ASTM D5988-12. ASTM International, West Conshohocken, PA.

Brodhagen, M., J. Goldberger, D. Hayes, D.A. Inglis, T. Marsh, and C. Miles. 2017. Policy considerations for limiting unintended residual plastic in agricultural soils. *Environmental Science and Policy* 69:81–84.

Brodhagen, M., M. Peyron, C. Miles, and D.A. Inglis. 2015. Biodegradable plastic agricultural mulches and key features of microbial degradation. *Applied Microbiology and Biotechnology* 99:1039-1056.

Corbin, A.T., C. Miles, J. Cowan, D. Hayes, J. Dorgan, and D. Inglis. 2013. Using biodegradable plastics as agricultural mulches. *Washington State University Extension Fact Sheet* FS103E. 15 Aug. 2017.

Cowan, J.S., C.A. Miles, P.K. Andres, and D.A. Inglis. 2014. Biodegradable mulch performed comparably to polyethylene in high tunnel tomato (*Solanum lycopersicum* L.) production. *Journal of the Science of Food and Agriculture* 94:1854-1864.

Closas, L.M. Professor of Horticulture, Department of Horticulture, Botanics and Gardening· Agricultural Ecobiotechnology, Universitat of Lleida Spain.

Eubeler, J.P., S. Zok, M. Bernhard, and T.P. Knepper. 2009. Environmental biodegradation of synthetic polymers I. Test methodologies and procedures. *TrAC Trends in Analytical Chemistry* 28:1057-1072.

Galinato, S.P., and T.W. Walters. 2012. Cost estimates of producing strawberries in a high tunnel in western Washington. *Washington State University Extension Publication* FS093E.

Galinato, S.P., C. Miles, and S. Ponnaluru. 2012. Cost estimates of producing fresh market field-grown tomato in western Washington. *Washington State University Extension Publication* FS080E.

Ghimire, S., and C. Miles. 2016. Dimensions and costs of polyethylene, paper and biodegradable plastic mulch. *Washington State University Extension Factsheet*. 15 Aug. 2017.

Ghimire, S., A.L. Wszelaki, J.C. Moore, D.A. Inglis, and C.A. Miles. 2018. Use of biodegradable mulches in pie pumpkin production. *Hortscience* 53:288-294

Ghimire, S., A. Saxton, A.L. Wszelaki, J.C. Moore, and C.A. Miles. 2017. Reliability of soil sampling method to assess visible biodegradable mulch fragments remaining in the field post soil-incorporation. *HortTechnology* 27:650-658.

Gilmore, D.F., S. Antoun, R.W. Lenz, and R.C. Fuller. 1993. Degradation of poly(hydroxyalkanoates) and polyolefin blends in a municipal wastewater treatment facility. *Journal of Polymers and the Environment* 1:269-274.

Hakkarainen, M., and A.C. Albertsson. 2004. Environmental degradation of polyethylene. *Advances in Polymer Science* 169:177-200.

Hayes, D., S. Dharmalingam, L. Wadsworth, K. Leonas, C. Miles, and D. Inglis. 2012. Biodegradable agricultural mulches derived from biopolymers, p. 201-222. In: K. Khemani and C. Scholz. eds. Degradable polymers and materials: Principles and practice, 2nd ed. ACS Symposium Series, Volume 1114. Oxford University Press, Washington, D.C.

Jamshidian, M., A. Tehrany, M. Imran, M. Jacquot, and S. Desobry. 2010. Poly-lactic acid: Production, applications, nanocomposites, and release studies. *Comprehensive Reviews in Food Science and Food Safety* 9:552–571.

Kasirajan, S., and M. Ngouajio. 2012. Polyethylene and biodegradable mulches for agricultural applications: A review. *Agronomy for Sustainable Development* 32:501-529.

Kawai, F. 1995. Breakdown of plastics and polymers by microorganisms. *Advances in Biochemical Engineering / Biotechnology* 52:151-94.

Khemani, K., and C. Scholz. 2012. Degradable polymers and materials: Principles and practice. 2nd ed. ACS Symposium Series, Volume 1114. Oxford Univ. Press, Washington, D.C.

Kim, D.Y., H.W. Kim, M.G. Chung, and Y.H. Rhee. 2007. Biosynthesis, modification, and biodegradation of bacterial medium-chain-length polyhydroxyalkanoates. *The Journal of Microbiology* 45:87-97.

Levitan, L. 2005. Reducing dioxin emissions by recycling agricultural plastics: Creating a viable alternative to open burning. In Great Lakes Regional Pollution Prevention Roundtable, NY.

Li, C., J. Moore-Kucera, C. Miles, K. Leonas, J. Lee, A. Corbin, and D. Inglis. 2014a. Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. *Agroecology and Sustainable Food Systems* 38:861-889.

Li, C.H., J. Moore-Kucera, J. Lee, A. Corbin, M. Brodhagen, C. Miles, and D. Inglis. 2014b. Effects of biodegradable mulch on soil quality. *Applied Soil Ecology* 79:59-69.

Liu, E.K., H.Q. He, and C.R. Yan. 2014. ‘White revolution’ to ‘white pollution’—agricultural plastic film mulch in China. *Environmental Research Letters* 9 091001.

MarketsandMarkets. 2012. Agricultural films market by applications and polymers — global trends and forecasts to 2017. MarketsandMarkets Research Private Ltd., Maharashtra, India.

Miles, C., L. DeVetter, S. Ghimire, and D. Hayes. 2017. Suitability of biodegradable plastic mulches for organic and sustainable agricultural production systems. *HortScience* 52:10-15.

Miles, C., R. Wallace, A. Wszelaki, J. Martin, J. Cowan, T. Walters, and D. Inglis. 2012. Deterioration of potentially biodegradable alternatives to black plastic mulch in three tomato production regions. *HortScience* 47:1270-1277.

Miles, C., S. Ponnaluru, S. Galinato, D. Inglis, T. Marsh, A. Corbin, K. Leonas, T. Walters, D. Hayes, B. Jones, J. Lee, L. Wadsworth, A. Wszelaki, J. Moore-Kucera, R. Wallace, M. Brodhagen, and E. Belasco. 2015. Glossary of terms associated with biodegradable mulches for specialty crops. 8 Aug. 2017.

Mohan, S.K., and T. Srivastava. 2010. Microbial deterioration and degradation of polymeric materials. *Journal of Biochemical Technology* 2:210-215.

Ohtake, Y., T. Kobayashi, H. Asabe, and N. Murakami.1998. Studies on biodegradation of LDPE-observation of LDPE films scattered in agricultural fields or in garden soil. *Polymer Degradation and Stability* 60:79-84.

OMRI. 2015. Report on biodegradable biobased mulch films. U.S. Dept. Agric., National Organic Program, Organic Materials Review Institute, Washington, D.C.

Reemmer, J. 2009. Advances in the synthesis and extraction of biodegradable poly- hydroxyalkanoates in plant systems. *MMG 445 Basic Biotechnology* 5:44-49.

Shanks, R., and I. Kong. 2012. Thermoplastic starch, p. 96-116. In: A. Z. El-Sonbati. ed. Thermoplastic Elastomers. InTech. Rijeka, Croatia.

Steinmetz, Z., C. Wollmann, M. Schaefer, C. Buchmann, J. David, J. Troger, K. Munoz, O. Fror, and G.E. Schaumann. 2016. Plastic mulching in agriculture: Trading short-term agronomic benefits for long-term soil degradation. *Science of the Total Environment* 550:690–705.

Swift, G. 1993. Directions for environmentally biodegradable polymer research. *Accounts of Chemical Research* 26:105-110.

USDA. 2012. Biodegradable mulch film made from bioplastics. Technical evaluation report compiled by ICF International for the USDA National Organic Program. Agriculture Marketing Service (AMS), United States Department of Agriculture, 20 June 2017.

USDA. 2013. Can GMOs be used in organic products? United States Department of Agriculture, Washington, D. C. 7 June 2016.

USDA. 2014. The national list of allowed and prohibited substances. United States Department of Agriculture, Washington, D. C. 7 June 2016.

USDA. 2015. Memorandum to the national organic standards board, 22 January 2015. National Organic Program. United States Department of Agriculture, Washington, D. C. 7 July 2016.

Wortman, S.E., I. Kadoma, and M.D. Crandall. 2016. Biodegradable plastic and fabric mulch performance in field and high tunnel cucumber production. *HortTechnology* 26:148-155.