Soil-Biodegradable Mulches: *Course Lecture*

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Synopsis:
Soil-biodegradable mulches (BDMs) are increasingly used in agriculture to replace conventional plastic mulch. This is an overview of all the aspects of BDM.

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USDA United States Department of Agriculture National Institute of Food and Agriculture

Soil-biodegradable Mulch in Agriculture

This course lecture provides slide presentations on soil-biodegradable mulches (BDMs). These notes provide additional information for presenters. Numbers in the text correspond to the slides in each presentation. Information in this document was summarized from publications listed in the Reference section.

1. This presentation provides information on the crop production with BDMs, standards, and feedstocks that define BDMs, application of BDMs, crop-weed competition and percent soil exposure (PSE) measurement, fumigation and BDMs, deterioration and degradation of BDMs, how to sample soil to measure visible plastic fragments, economics of BDM use, and sociological perceptions with BDM.
2. Polyethylene (PE) mulch has been in use since 1950s to manage weeds, conserve moisture, warm soil, increase yield, and increase crop quality. Plastic mulch use in North America was 115,000 metric ton in 2016 and the estimated use in 2020 is 126,400 metric ton. Globally, the mulch film market has an annual projected growth rate of 7.4% from 2018 to 2026. In 2019 the mulch film market was approximately 4.3 billion dollars in 2019.
3. BDM is an alternative to PE mulch as it provides comparable crop production benefits: weed control, moisture retention, soil temperature modification, early harvest,

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increased yield and quality. BDMs are designed to be tilled into the soil after use, eliminating waste and disposal challenges. Note that BDMs should NOT go into recycling facilities as they will contaminate other recycled material.

4. Crop production with BDMs is shown in Table 1. Yield is greater compared with bare ground and essentially the same as with PE mulch. Weed control varies between BDM and PE mulch depending on crop and location.

5. ASTM and ISO standards pertaining to biodegradable plastics are not specific to mulch. ASTM D6400 is one of the most commonly cited standards in reference to BDMs. Biodegradation under ASTM D6400 is tested under composting conditions. This standard employs a standardized test method, ASTM D5338, which utilizes a laboratory test that simulates industrial composting conditions: the use of a compost-based medium, 58°C, etc. European Standard EN 17033 released by the European Committee for Standardization (CEN) in January 2018 was the first standard put forth for certification of biodegradable plastic mulch films. Its requirements regulate composition, biodegradability in soil, and ecotoxicity, as well as dimensional, mechanical and optical properties; and test procedures are included for each. A major criterion of EN 17033 is the requirement of ≥90% biodegradation under aerobic conditions in a natural topsoil from an agricultural field or forest at 20 to 28°C conditions within 2 years, using a standardized test to measure CO_2 evolution. The reasons that 90% biodegradation and not 100% is used as a criterion in standards is that a) a significant portion of the plastic incorporated into microbial biomass is difficult to measure, and b) the limited precision of biodegradability lab tests.

Table 1. Crop production with BDM

	Yield		Weed Control
Crop	**vs. Bare ground**	**vs. PE**	**vs. PE**
Broccoli	+[1]		
Cucumber	+	=	=
Eggplant	+	=	-
Lettuce		-=[2]	
Melon	+	+=	≅
Pepper	=	=	-
Raspberry	+	=	=
Strawberry	+	-=+[2]	-
Sweet Corn	+	-=	-
Sweet Potato	+	+=	+
Tomato	+	=	≅
Zucchini		=	

[1] + BDM performed better; = BDM performed equivalent to; - BDM did not perform as well; empty cell not measured.

[2] Reports provide variable results.

Adapted from: Cowan and Miles, 2018

6. BDMs are made from feedstocks that are: (i) biobased, (ii) derived from fossil fuels, or (iii) a blend of the two. Biobased polymers are divided into 3 categories (Table 2): **a)** extracted directly from natural materials such as starch, thermoplastic starch (TPS), and cellulose; **b)** produced by chemical synthesis from biologically derived monomers, such as synthetic polymerization of lactic acid into polylactic acid (PLA); and **c)** produced by microorganisms, such as polyhydroxyalkanoates (PHA). Most common biobased BDM feedstocks are TPS, PLA, and PHA. High-amylose starch is processed into TPS by extrusion with water and alcohols at relatively high temperatures. TPS costs less than other starch feedstocks and now is the most common biobased feedstock used in plastic BDMs. PLA can be produced relatively inexpensively in large quantities compared to other biobased biopolymers. Poly (hydroxy-butyrate) (PHB) and poly (hydroxyvalerate) (PHV) are the two most important commercial PHAs. Polymers such as PLA or PHA have low mechanical properties compared to PE. Plasticizers are additives which improve the mechanical properties of the plastic during processing, and can affect post-extrusion characteristics of the plastic. The primary plasticizers that are added to TPS are alcohol (principally glycerol), polyoxyalkenes, and surfactants.
7. Oxo- and photo-degradable plastics are made with conventional plastic: HDPE, LDPE, PP, PS, PET or PVC. Also included are additives that cause the material to become brittle and break apart into fragments when exposed to UV light, heat and/or oxygen (Figure 1). Oxo- and photo -degradable mulches are not biodegradable, compostable, or recyclable, and cannot be placed in anaerobic digesters. There is a resurgence in their use, due to the interest in BDMs and large price difference between BDMs and oxo- and photo-degradable mulches. The European Union (EU) will prohibit single-use plastic products and products made from oxo-degradable plastic, European Parliament Directive 2019/904 Article 5, 5 June 2019, to be applied by 3 July, 2021.
8. The USDA National Organic Program added biodegradable biobased mulch film to its list of allowed substances in October

Table 2. Categories of biobased polymer feedstocks.

Extracted from natural materials	Produced by chemical synthesis	Produced by microorganisms
starch, thermoplastic starch (TPS), and cellulose	synthetic polymerization of lactic acid into polylactic acid (PLA)	polyhydroxyalkanoates (PHA)
TPS processed from high-amylose starch, cheaper than other starch feedstocks	PLA produced relatively inexpensively compared to other biobased biopolymers	Poly(hydroxybutyrate) (PHB) and poly(hydroxyvalerate) (PHV) most important commercial PHAs

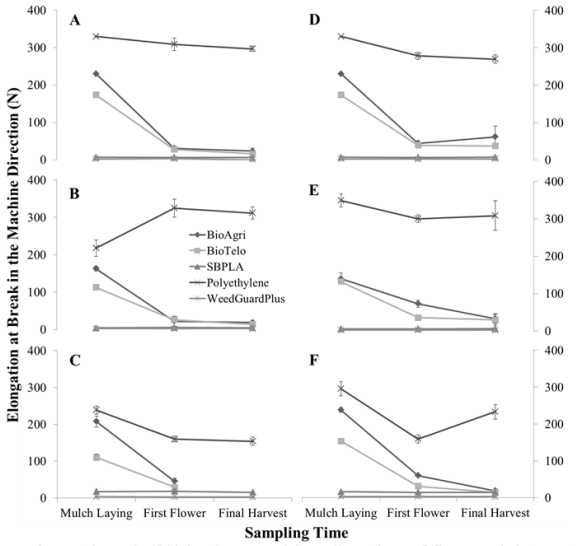
Figure. 1. Oxo- and photo-degradable plastic includes additives that cause the material to turn brittle and break into fragments when exposed to UV light, heat, and/or oxygen.

2014. However, it **MUST**: **a)** be 100% biobased (*ASTM D6866)*; **b)** be produced without use of synthetic polymers (minor additives such as colorants and processing aids not required to be biobased); **c)** be produced without organisms or feedstock derived from excluded methods (i.e., synthetic or GMO); **d)** meet compostability specifications (ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088); and **e)** reach ≥ 90% degradation in soil within 2 years (*ISO 17556* or *ASTM D5988)*.

9. What does the label tell you? If biodegradability test results are not included in the product label, then it should be assumed that the product does not meet the standards.

10. BDMs are usually thinner than PE mulch. Reducing the thickness of BDM reduces their cost. Mechanical strength, measured as elongation, breaking force and split force are greater for PE than BDM (Fig. 2).

11. Mulch and drip tape can be laid simultaneously (Fig. 3). Mulch is usually 3—5 ft in width; bed width and height are adjustable; release the tension on the roller bars that press down on the mulch before applying.



Elongation at break (%) in the machine direction of five mulch treatments (BioAgri, BioTelo, SBPLA, polyethylene, and WeedGuardPlus) in open field (**A**–**C**) and high tunnel (**D**–**F**) tomato production, Mount Vernon, WA, in 2010 (**A** & **D**), 2011 (**B** & **E**), and 2012 (**C** & **F**). Error bar is ± one standard error of the mean.

Figure. 2. Mulch properties of PE vs. BDM

12. Mulch layers can be flat-bed (Fig. 4), raised bed (Fig. 5) or multiple beds wide as in this 3-row layer (Fig. 6).

13. The same equipment i.e. mulch layer is used to apply both PE mulch and BDM. The procedure for mulch laying is similar for all mulch layers. First feed the end of the mulch roll through the roller bar and reduce the tension so it can roll easily (Fig. 7). Pull the mulch under the guide wheels; the wheel(s) should rest lightly on the mulch or float just above it (Fig. 8). Place the drip tape roll in the desired location (i.e. center of bed) and secure the roll. Shovel soil onto the end of the mulch at the end of the bed and on the sides under the wheel to keep the mulch in place before pulling it. Secure the drip tape at the end of the row. Slowly drive the tractor forward, gradually increasing the speed. After laying a row, cut off the mulch from the roll and cut the drip tape. Secure the mulch at the end of the row by covering the mulch with soil (Fig. 9). If the mulch tears in the middle of laying a row, cover the rip with soil. Or if the ripping is across the bed, stop laying the mulch, pull the mulch off the roll to overlap about 1 foot with the mulch on the bed, and continue laying.

14. Weed control is the primary function of mulch. Weeds compete with the main crop for nutrients, water, and light which causes adverse effects on crop growth. PE mulch is very effective for weed control, but what about BDMs?

Figure 3. Mulch and drip tape can be laid simultaneously; note the round drum of drip tape on the left above, and the roll of mulch on the right.

Figure 4. Flat-bed layer.

Figure 5. Raised-bed layer (RainFlo D2600).

Figure 6. Multiple bed layer (RainFlo D2600).

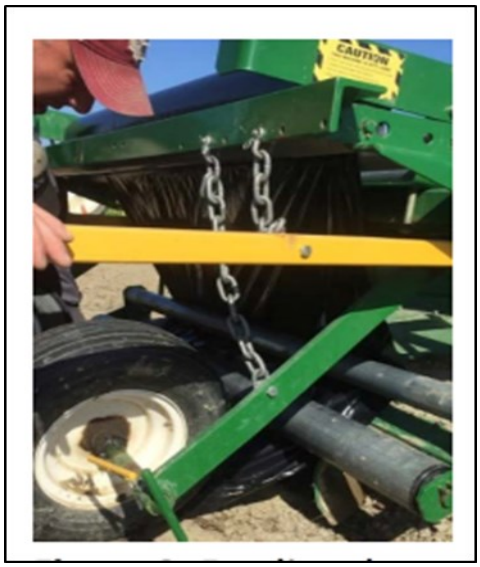


Figure 7. Feed mulch through roller bar; adjust tension.

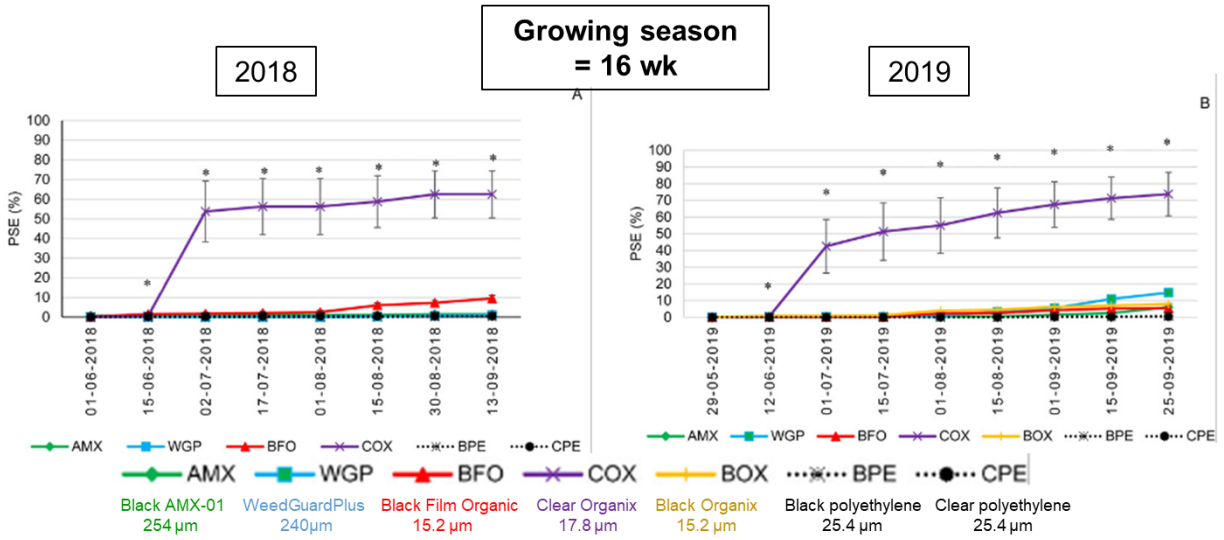
Figure 9. Secure the mulch at the end of the row by covering mulch with soil.

15. The graphs (Fig. 10) show the percent soil exposure (PSE) during the pumpkin growing season of about 16 weeks in Mount Vernon, WA in 2018 and 2019. When the mulch deteriorates, the soil gets exposed and there is potential for weed growth. 0% PSE denotes completely intact mulch while 100% PSE denotes completely deteriorated mulch. Ratings were in 1% increments up to 20% PSE, and in 5% increments thereafter. PSE was highest for Clear Organix mulch in both years (63% in 2018, and 74% in 2019). All other BDMs reached a maximum of 10% PSE in 2018 and 15% in 2019.

Figure 8. Pull mulch under guide wheels.

16. This table (Table 3) shows the weed population per m^2 under mulch at three different times, early season, mid-season, and late season in 2018 and 2019. Weed number was low for all the treatments except Clear Organix mulch (COX) in 2018 and 2019 plus Clear polyethylene mulch (CPE) in 2019. Weed growth occurred beneath the clear plastic mulch treatments because they allowed light transmission. However, weeds continued to grow in Clear Organix mulch (COX) due to splitting early in the season. The higher weed number in Clear polyethylene mulch (CPE) in 2019 was likely due to higher soil moisture than in 2018. Weed growth in late season was due to mulch deterioration. Other BDM treatments provided effective weed control similar to black polyethylene mulch.
17. This (Fig. 11) is how Black Organix mulch (BOX) and Black polyethylene mulch (BPE) look in July 2019 and October 2019 in pumpkin. They are both intact with essentially no weeds.
18. Soil fumigation is an important operation to manage soilborne diseases, parasitic nematodes, certain arthropod pests, and weeds. Tarping with totally or virtually impermeable films (TIF and VIF tarps) improves efficacy and reduces buffer zones.

19. EPA has list of tarps tested for permeability that qualify for buffer zone reduction credits. Like standard PE tarps, BDMs are not currently on this list. Applicators and handlers need to be legally consistent with fumigant labels. BDMs can only be applied after the fumigant's REI has expired or BDMs may be applied during fumigation but don't qualify for buffer zone reduction credits.



Zhang et al., 2020

Figure 10. PSE during pumpkin growing season in Mount Vernon, WA; 0% = completely intact, 100% = fully deteriorated, ratings in 1% increments up to 20%, and 5% increments thereafter; error bar is ± one standard error of the mean. 25.4 µm = 1 mil.

Table 3. Weed population per m² under mulch in pumpkin.

	Weed number per m²					
	2018			2019		
Treatment	Early season (3 WAT[z])	Mid-season (10 WAT)	Late season (15 WAT)	Early season (3 WAT)	Mid season (10 WAT)	Late season (16 WAT)
AMX	0 b[y]	0 b	0.5 b	2.3 ab	0 b	0.3 bc
WGP	0 b	0 b	0 b	2.0 ab	0 b	4.0 b
BFO	0 b	0 b	0.8 b	1.3 ab	0 b	0 c
COX	2.0 a	10.0 b	21.0 a	6.8 a	77.5 a	89.5 a
BOX	—[x]	—	—	7.0 a	0 b	0.3 bc
BPE	0 b	0 b	0 b	0.3 b	0 b	0 c
CPE	2.5 a	0 b	0.5 b	2.3 a	16.5 ab	39.0 a
P value	0.04	0.03	0.03	0.02	0.02	0.02

[z]Weeds were collected 3 weeks after transplanting (WAT; 22 June 2018 and 20 June 2019), 10 WAT (9 Aug. 2018 and 8 Aug. 2019), 15 WAT (14 Sept.) in 2018, and 16 WAT (26 Sept.) in 2019.
[y]Means followed by the same letter in the same column are not significantly different at $P < 0.05$, using a nonparametric multiple comparisons Wilcoxon test.
[x]This treatment was not included in 2018.

Weed number per m² in plots with 'Cinnamon Girl' pie pumpkin grown with clear and black polyethylene (CPE and BPE) and soil-biodegradable mulch treatments [AMX-01 (AMX), WeedGuardPlus (WGP), Black Film Organic (BFO), Clear Organix (COX), and Black Organix (BOX)] in 2018 and 2019.

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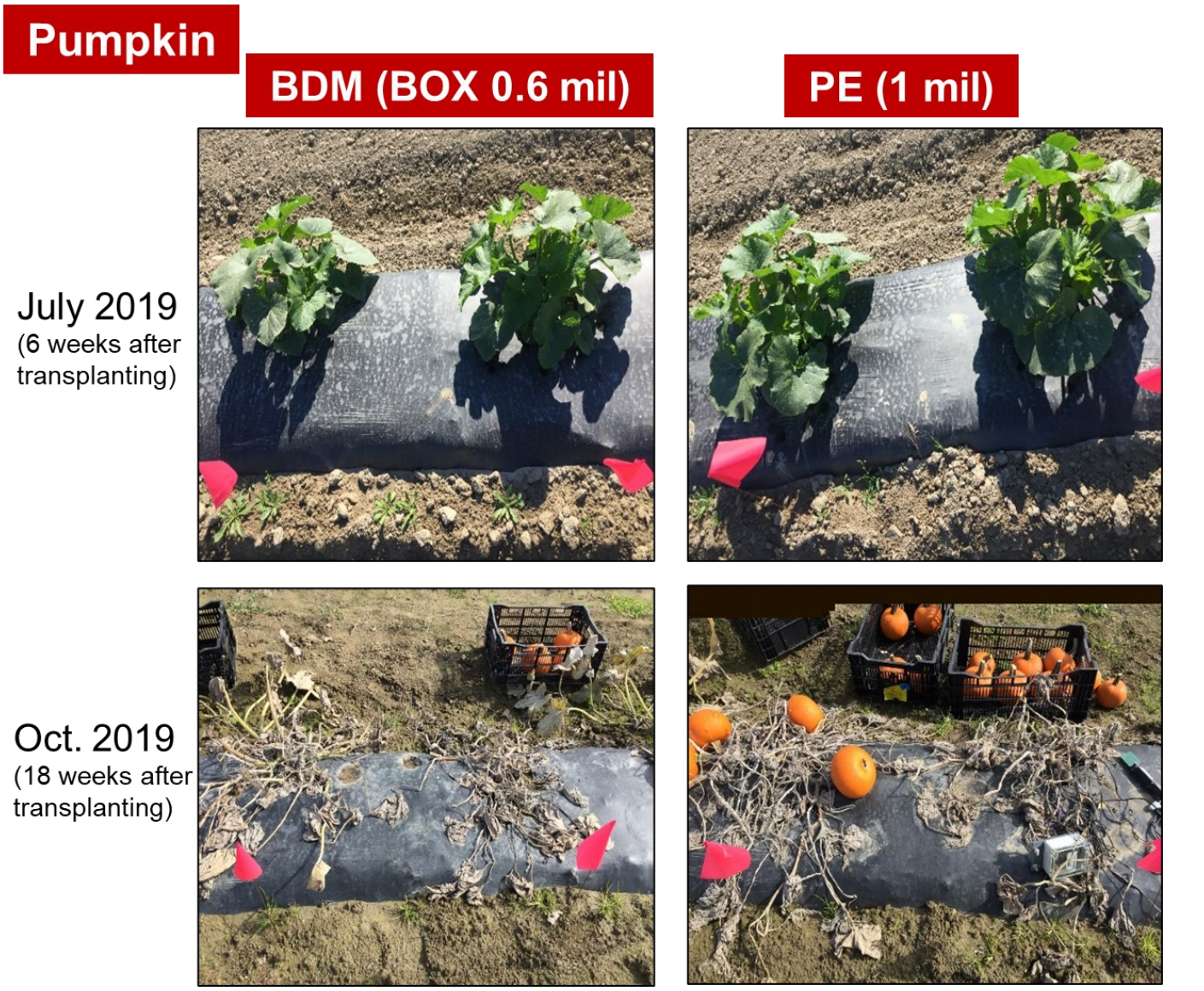


Zhang et al., 2020

Figure 11. Comparison of BDM (BOX) and PE mulch during pumpkin production.

20. Lets discuss about deterioration, degradation, and tillage of BDM.
21. The given picture (Fig. 12) shows mulch deterioration with different types of BDMs and PE mulch in sweet corn. Clear Organix plastic mulch and Weedguard plus shows some deterioration while other black plastic BDMs look intact similar to PE mulch.
22. Mulch deterioration can be assessed as percent soil exposure (PSE) where 0% represents completely intact mulch and 100% represents fully exposed soil. These pictures (Fig. 13) show 5% and 40% PSE.

23. **Deterioration** is loss of physical or mechanical strength, observed through physical testing, microscopic imaging, or macroscopic observation (e.g. rips, tears, and holes). **Degradation** is the conversion or mineralization of carbon (C) to carbon dioxide (CO_2) resulting in changes in the chemical structure, physical properties or appearance. ASTM defines biodegradable plastics as plastics that degrade from the action of naturally resulting organisms such as bacteria, fungi and algae. Polyethylene mulch (PE) is not readily biodegradable as polymers have chemical bonds that microbes do not have the metabolic pathways to break apart. Biodegradable plastics use natural or synthetic polymers that have similar bonds, but can be quickly broken apart by

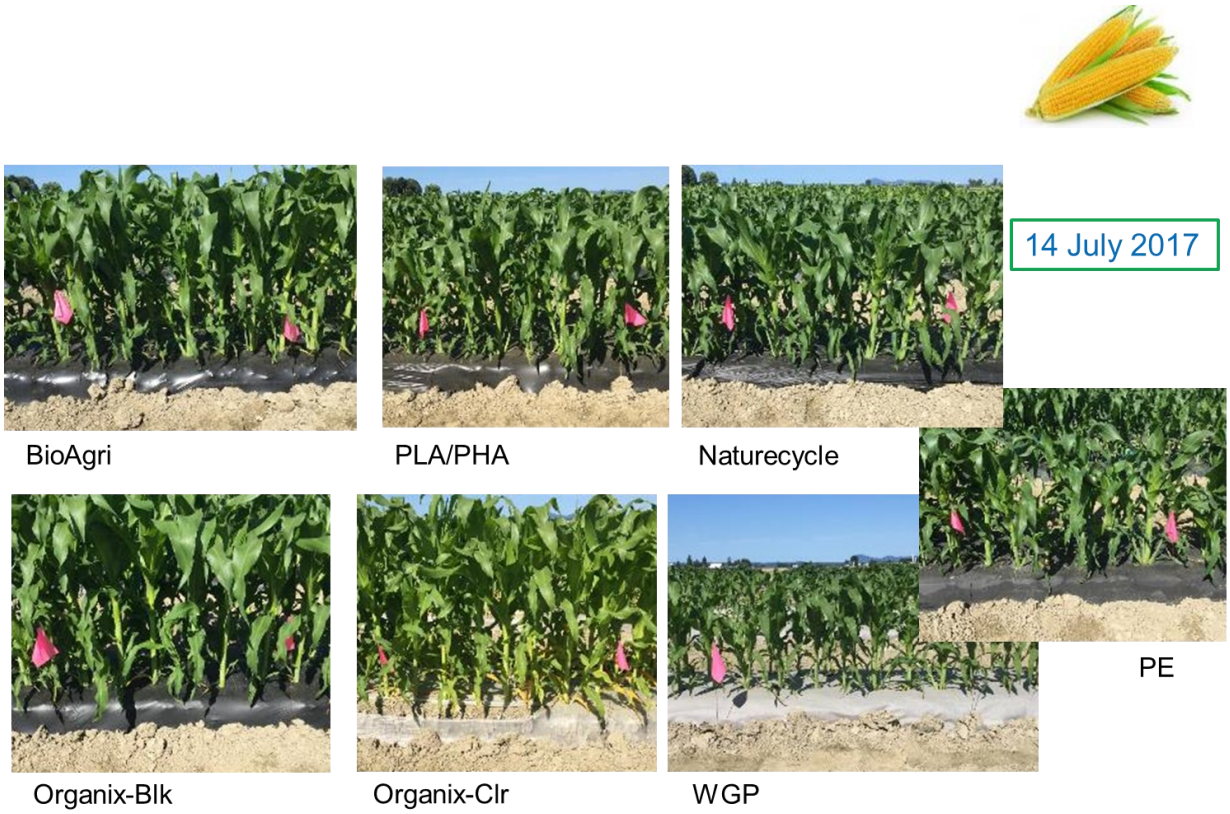


Figure 12. Mulch deterioration with different types of mulches.

Figure 13. Different ratings of PSE.

microbes.

24. Visual assessment of deterioration is measured as a decrease in mulch area—percent soil exposure (PSE), photography, colorimetry, macroscopic and microscopic examination, including scanning electron and laser confocal microscopy (Fig. 14).

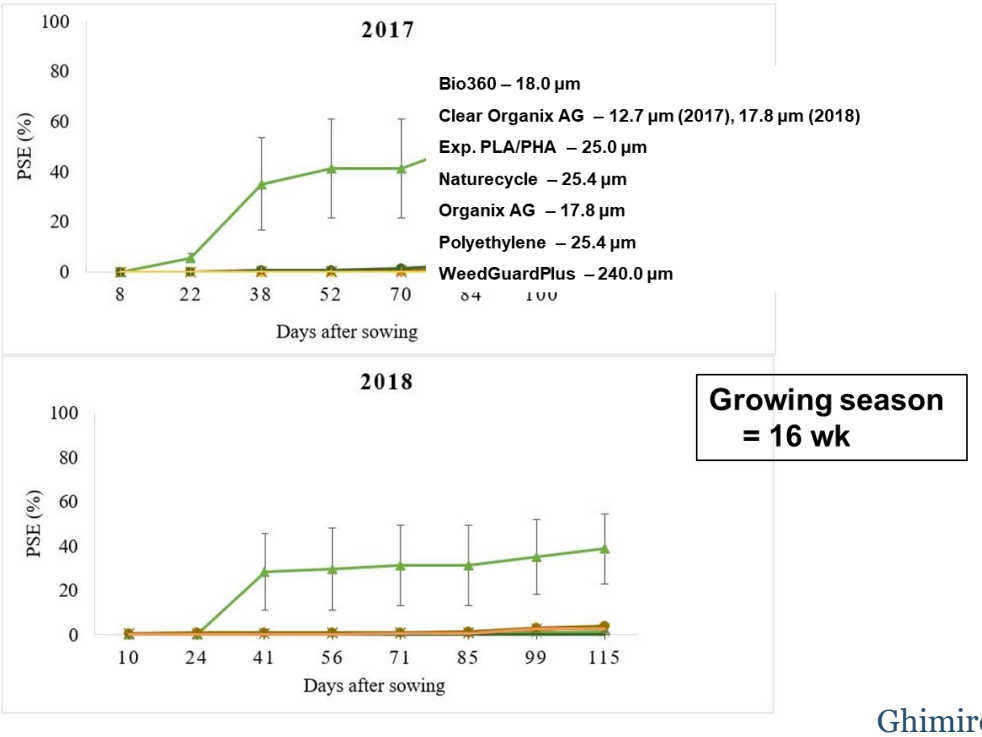
25. The graph (Fig. 15) shows the PSE during the sweet corn growing season of about 16 weeks in Mount Vernon, WA in 2017 and 2018. Zero PSE denotes completely intact mulch while 100% PSE denotes completely deteriorated mulch. Ratings were in 1% increments up to 20% PSE, and in 5% increments thereafter. PSE was highest for Clear Organix AG mulch and reached 51% and 39% by the end of the season in 2017 and 2018. Other black plastic BDMs and PE mulch had minimal (<5%) deterioration throughout the growing season in both years.

26. This graph (Fig. 16) represents the PSE for a period of 1 year during raspberry production in Lynden, WA. All the black plastic BDMs reached about 90% PSE in one year while PE mulch remained almost completely intact. At 16 weeks after mulch application, all the BDMs had less than 10% PSE which is similar to the sweet corn experiment (<5%). The black BDMs used in sweet corn production were thicker than the BDMs used in raspberry production.

27. The degradation process takes place sequentially from film to fragment to micro -particles to nano-particles to the final stage of CO_2 + biomass in the soil. A human hair demonstrates the relative size of microns and nanometers (Fig. 17). On average, thickness of PE mulch and BDMs range between 12 to 37 microns which is approximately equal to 0.5 to 1 mil.

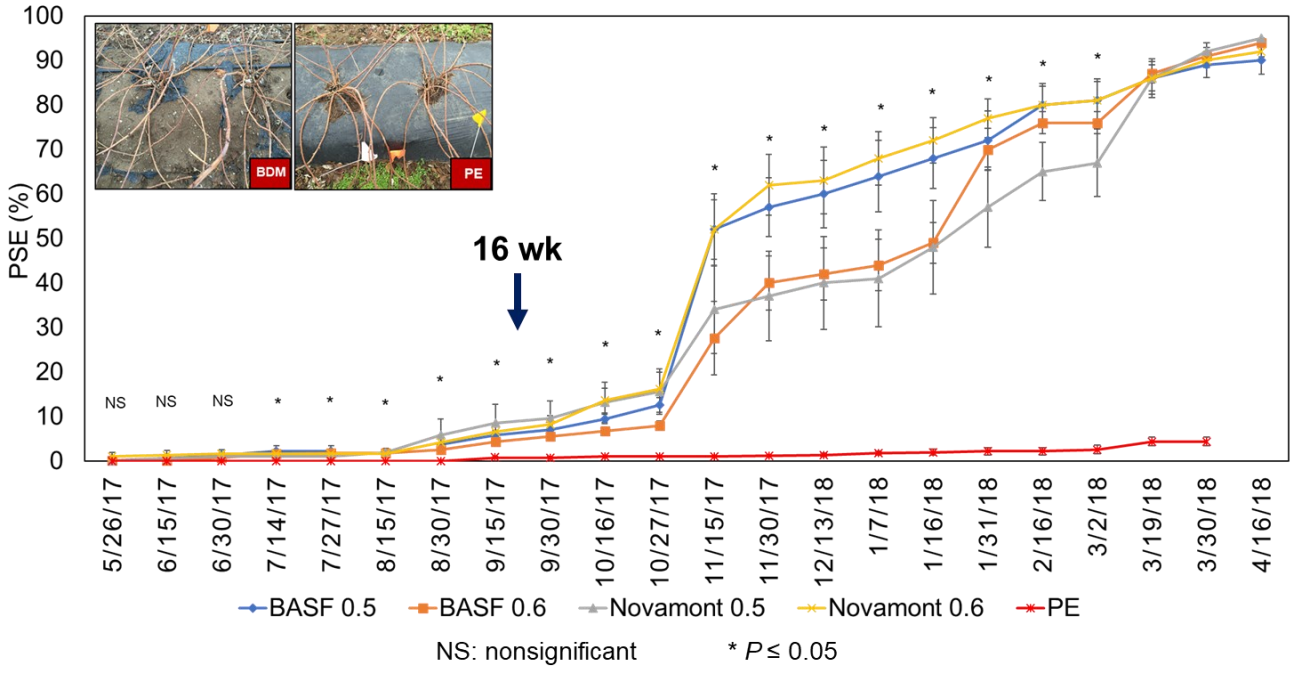
28. The graph (Fig. 18) shows the percent mulch recovery in Mount Vernon, WA using the soil quartering method after incorporation in the field. Mulch was applied once a year for 4 years (2015 - 2018). Plots were rototilled in spring after collecting samples and in fall before collecting samples. Paper BDM (WeedGuardPlus) shows complete biodegradation each year while other plastic BDMs have different rates of biodegradation. One year after the last soil-incorporation of BDM, recovery ranges from 10% to 30%, indicating that all of

Figure 14. Visually assess deterioration by estimating percent soil exposure (PSE) due to rips, tears, or holes (left and center); scanning electron microscope (SEM) image to assess deterioration on a microscopic level.



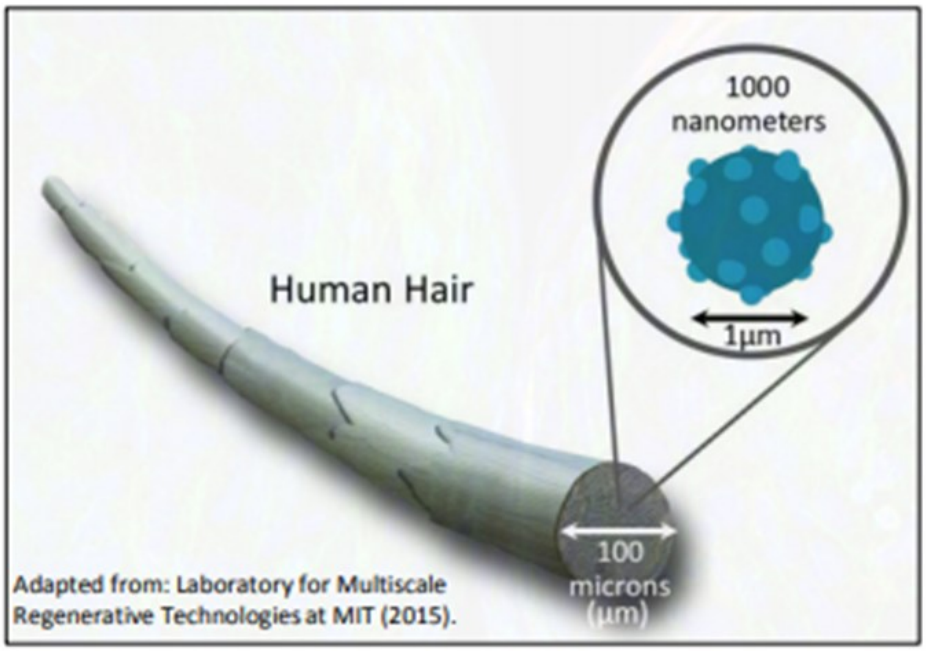
Ghimire et al., 2020a

Figure 15. PSE during sweet corn growing season in Mount Vernon, WA; 0 = completely intact, 100 = fully deteriorated, ratings in 1% increments up to 20%, and 5% increments thereafter; error bar is ± one standard error of the mean.



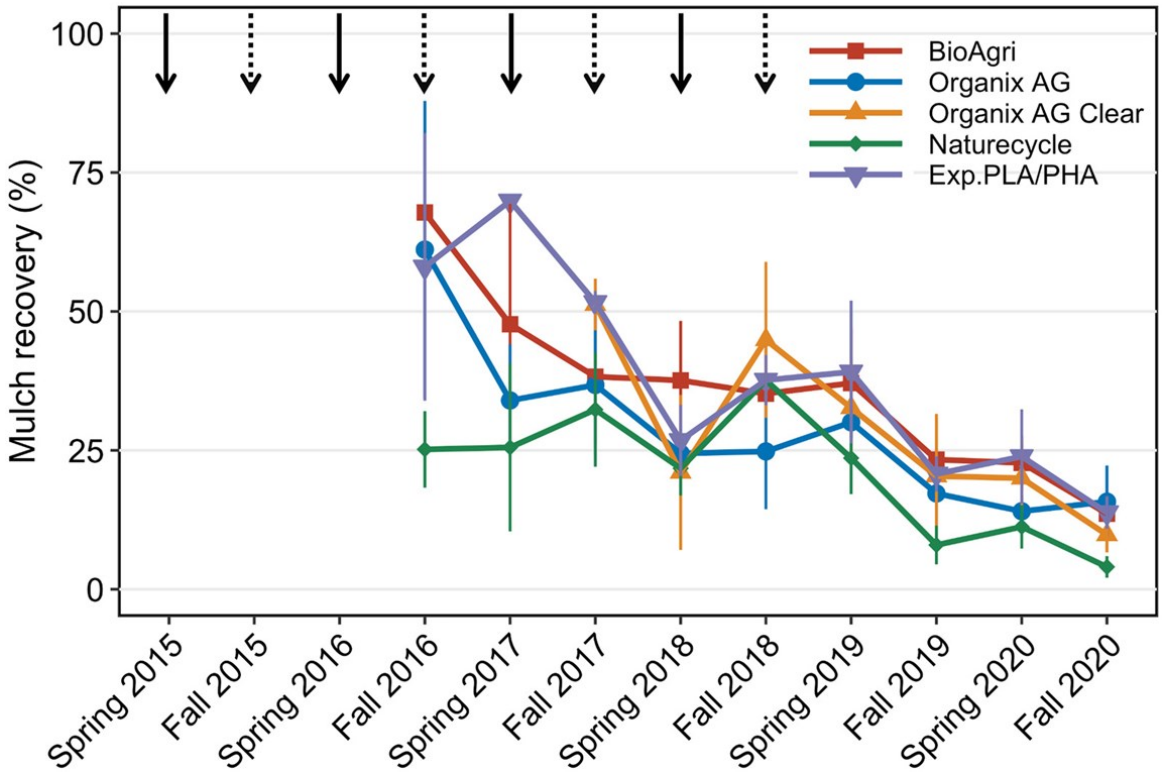
Zhang et al., 2020

Figure 16. PSE of mulch (0.5 = 12.7 µm thickness, 0.6 = 15.2 µm thickness) in raspberry production in Lynden, WA; 0% = completely intact, 100% = fully deteriorated, ratings in 1% increments up to 20%, and 5% increments thereafter; error bar is ± one standard error of the mean.



Hayes, 2019

Figure 17. A human hair demonstrates the relative size of microns and nanometers.



Griffin-LaHue et al., 2022

Figure 18. Percent recovery of BDM fragments in Mount Vernon, WA using the soil quartering method; mulch was applied once a year for 4 years (2015-2018), indicated by solid black arrows, plots were rototilled in spring after collecting samples and in fall before collecting samples, indicated by dotted arrows; error bar is ± one standard error of the mean.

these BDMs are degrading at this field site.

29. Now, lets discuss about how to sample soil for measuring visible plastic fragments post tillage.

30. Soil sampling is used to measure visible mulch fragments and is a measure of initial degradation. It is not a direct measure of the rate or extent of biodegradation. This sampling procedure does not distinguish between polyethylene (PE) and BDM. If PE mulch is in the soil, it is necessary to estimate its amount prior to BDM application.

31. Here is the link to the video that shows the method of soil sampling to measure visible plastic fragments.

32. Let's look at the economics of soil-biodegradable mulch use.

33. To estimate changes in net profits for PE mulch and BDM, we will evaluate the factors affecting the economic feasibility of 1 acre of a vegetable crop grown using a 6 ft space between bed centers. 1) Two 4x4000 ft rolls of mulch are needed to cover a 1 acre field.2) the cost of 1 4x4000 ft roll of 1 mil PE mulch is $111 and $220 for 0.6 mil plastic BDM, based on information from various input suppliers. 3) Labor cost is around $14.29 based on the New England and New York regions 2020 estimated adverse effect wage rate. 4) Disposal cost is $85/ton based on information from the Connecticut area. 5) Based on a survey of Tennessee fruit and vegetable farmers, 17.25 hours/acre are needed for PE mulch removal and disposal, and the removal of drip tape before tilling BDM into the soil takes 1.5 hours/acre. 6) Based on these assumptions, using plastic BDM instead of PE mulch will have a positive impact on net profits of about $18 per acre.

34. In the next few slides, we will discuss how changes in profits vary when costs for BDM and labor change. In this first figure, we have cost of BDMs on the horizontal axis and the change in profit on the vertical axis. As you can see in this graph (Fig. 19), as the price of a BDM roll increases, the profitability of using BDM decreases. For example, when a BDM roll costs $220, profit is $18 per acre when using BDM, but when the cost is $240/roll, there is a loss of $22 per acre compared with PE mulch. This result is important, as shipping costs will affect the base BDM price and could have a significant if local input suppliers do not carry

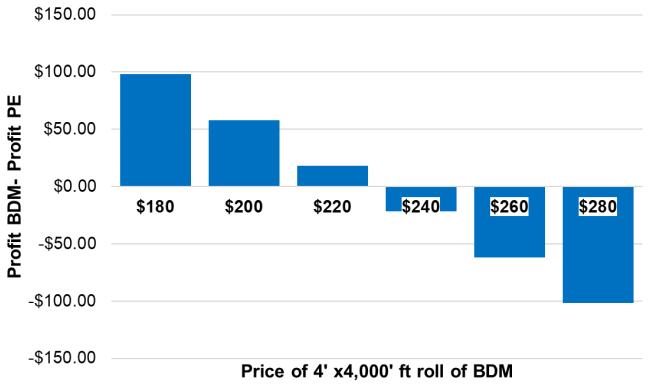


Figure 19. Sensitivity analysis of profit due to change in BDM cost.

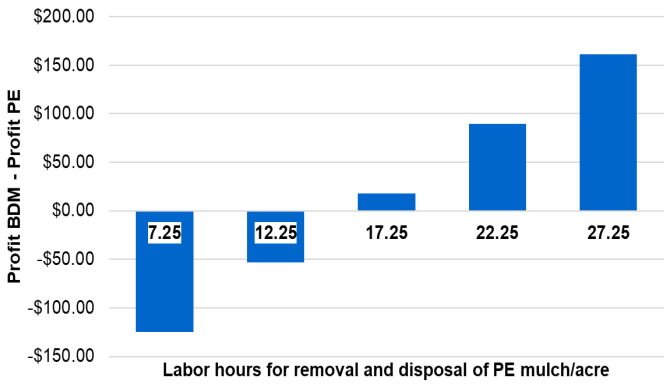


Figure 20. Sensitivity analysis of profit due to change in labor hours for removal and disposal of PE mulch.

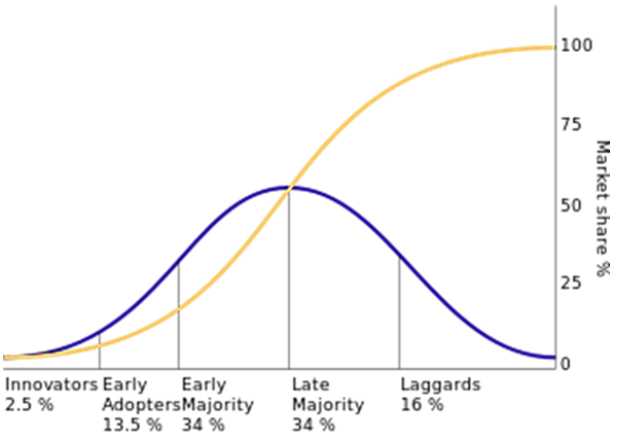
BDM.

35. Now, lets evaluate potential changes in profits for various scenarios of the number of labor hours per acre for removal and disposal of PE mulch. In this graph (Fig. 20), you can see that as the number of labor hours associated with removal and disposal activities increases, the likelihood of experiencing a positive impact on net profit when using BDM also increases. For example, if 12.25 labor hours per acre are needed for PE mulch removal and disposal, the profits associated with using BDM are about $53 lower than the profits associated with the use of PE mulch.

36. In summary, the cost of labor and BDMs are critical in assessing whether the use of BDMs is economically feasible for a farm. In small operations, the farm owner is often responsible for performing cleanup activities at the end of the season and these hours are often not considered a direct cash expense and may be overlooked when estimating total labor costs. Calculating the value of this unpaid labor will help assess the monetary value of the end-of-season activities and will also help plan for future scenarios where owners may not be physically able to do this job. For farms using migrant workers, although labor savings are important, it is also important to know the implications of reducing end-of-season activities or letting workers leave the farm early. If their labor hours are reduced, workers may decide to go to another farm that will employ them for more hours per season. Therefore, it is essential for the farmer to be aware of the unintended consequences of reducing workers' hours at the end of the season.

37. Let's discuss about perceptions and experiences of growers with BDM.

38. Sociology is the study of society, human behavior, and relationships. It allows us to explore perceptions, experiences, and adoption of new technologies or innovations. BDMs are a new technology. There are five established adopter categories: innovators, early adopters, early majority, late majority, and laggards. The majority of the population tends to fall in the middle categories. People in the 'early majority' category need to see evidence of the innovation's effectiveness while people in the 'late majority' category will only adopt an



innovation after it has been tried by the majority.

39. In a survey of 227 US strawberry growers in 2016, growers' perceptions and experiences with plastic mulches were assessed. 52% of respondents agreed that BDMs are environmentally friendly. 41% of respondents agreed they are interested in using biodegradable plastic mulch films.

40. Respondents were asked about their opinions on BDMs in the survey. When asked what they liked most about using BDM in their strawberry fields, 33% of survey respondents mentioned the lack of need to remove/dispose of the mulch films, 20% mentioned about healthy/ clean plants, 13% mentioned weed control, and 13% mentioned about biodegradability. When asked what they liked least, 53% of respondents mentioned that the mulch films break down too quickly, 20% mentioned that BDMs degrade une-

venly within fields or season-to-season, and 20% mentioned that BDMs are expensive.

41. On-farm trials with watermelon, winter squash, and cut flowers achieved good crop quality and yield with BDMs. BDMs visibly degraded. Farm owner and operators, who were concerned about BDM fragments looking like non-biodegradable plastic when tilled down in the fall, were pleased with how the BDMs had broken down in the following spring. They found few scraps remaining in the soil. Plastic BDMs were preferred over PE and paper mulch, and were considered more environmentally friendly. Growers were concerned about aesthetics of plastic BDMs (which look like PE mulch), soil health over time, and fear that customers may have negative connotations to the word "plastic" even if it's biodegradable.

42. For more information and references you can visit our website.