Building Agricultural Knowledge of Soil-biodegradable Plastic Mulch

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ABSTRACT. The use of polyethylene (PE) mulch causes environmental pollution where incomplete removal leaves fragments susceptible to escape to ecosystems, such as the ocean, where they can cause ecological harm. PE mulch is generally nonrecyclable due to contamination with soil and crop debris after use, leaving growers with few end-of-life options for used PE mulch. Research studies have shown that soil-biodegradable plastic mulch (BDM) is comparable to PE mulch in terms of performance, soil health, and overall economics and is preferred from an environmental perspective, but the adoption of BDM by producers is still low. Previous research has shown that the primary barriers to BDM adoption are insufficient knowledge about BDM, high purchase cost, and unpredictable breakdown of BDM in the soil. The high purchase cost of BDM compared with PE mulch is offset by the costs for PE mulch removal, transport, and disposal fees. This project was conducted to develop BDM training materials, to educate and assess BDM knowledge gained by extension personnel and other agricultural professionals through trainings and webinars, and to educate producers about BDM through hands-on experience. Thirty-six research and extension publication outputs from two previous US Department of Agriculture Specialty Crop Research Initiative BDM projects were reviewed and transcribed into 45 new extension publications that included 11 slide presentations, 5 lecture slides, 10 fact sheets, and 3 videos. All the training materials are posted on a public university website. Professional development trainings were conducted at local, regional, national, and international levels to provide agricultural professionals the current, science-based information on BDM and resources for information. Survey results showed that at a local level, the greatest change of knowledge among participants was observed for "BDM use in organic production" (60%), and the lowest reported change of knowledge was observed for "limitations to PE mulch disposal" (19%). At a regional level, out of 58 participants, 23% to 35% of participants learned "a lot" and 35% to 51% learned "some new information" regarding BDM from the webinar. At the national level, out of 30 participants, 48% responded that they learned "a lot" and another 48% learned "some new information" on BDM from the training. Growers were trained about BDM via field days and on-farm demonstrations where five strawberry (*Fragaria ×ananassa*) growers volunteered to participate in BDM trials. The participant growers observed no difference in weed control and fruit yield between the PE mulch and the BDM. Growers expressed concerns about slow biodegradation of BDM after soil incorporation, potential impacts on soil biological activity, food safety concerns with BDM fragments and that BDM is not currently permitted for use in organic production.

The United States uses ~0.37 million tonnes of agricultural plastics annually in the form of mulch, irrigation tubing, ditch lining, animal fencing, fumigation tarp, nursery containers, and pesticide containers (Jones 2018). The global demand for greenhouse, mulching, and silage films is expected to increase by 50% from 6.1 million tonnes in 2018 to 9.5 million tonnes in 2030 (Food and Agriculture Organization of the United Nations 2021). PE mulch, a thin non-biodegradable plastic film, has been commercially used in agriculture for ~60 years and provides benefits such as weed control, soil temperature modification, and soil moisture retention, thereby increasing crop yield and quality (Ibarra et al. 2001; Kasirajan and Ngouajio 2012; Lamont 2005). Despite these benefits, the use of PE mulch can cause environmental pollution because it is generally nonrecyclable due to contamination with soil and crop debris after use (Kasirajan and Ngouajio 2012). This leaves growers with few end-of-life options for used PE mulch. Most growers dispose of their used PE mulch into landfills; some growers stockpile it, burn it on-site, or even bury it in the soil (Goldberger et al. 2019; Kasirajan and Ngouajio 2012). Fragments of PE mulch are usually left in the soil during mulch retrieval, which can threaten soil quality and pollute the environment if it migrates off-site (Liu et al. 2018; Lwanga et al. 2022; Xu et al. 2020).

Comprehensive studies have analyzed how BDM compares to PE mulch from performance, soil health, economic, and environmental perspectives. The European standard EN 17033 is used to verify that a BDM is 100% soil-biodegradable (Hayes and Flury 2018), and this test can be third-party verified, for example, by the Biodegradable Products Institute (New York, NY, USA). Research has shown that BDM performs comparably to PE mulch in suppressing weeds, moderating soil temperatures, and increasing crop yields despite some breakdown of BDMs during the growing season (Cowan et al. 2014; Ghimire et al. 2018; Tofanelli and Wortman 2020). In a 6-year field study in China, BDMs did not negatively impact soil quality; rather, their use was associated with increased soil microbial activity and soil fertility (Zhang et al. 2022). In a study carried out in both a humid subtropical region and a cool Mediterranean region, 4 years of continuous use of BDM had similar effects as PE mulch on soil and groundwater quality (Sintim et al. 2021). From an economic perspective, BDM purchase cost is greater than PE mulch; however, BDM is tilled into soil, saving on removal and disposal costs, and thus BDM can be more economical overall than PE mulch (Velandia

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.0254	mil(s)	mm	39.3701
0.9072	ton(s)	tonne(s)	1.1023

et al. 2020). The replacement of PE mulches with BDMs promotes more sustainable cultivation through reduction of plastic contamination of soil and plastic pollution in the environment (Hayes et al. 2019). Despite these advantages, the adoption of BDM appears to be less than 10% among growers (DeVetter et al. 2021; Goldberger et al. 2019; Madrid et al. 2022).

An assessment carried out by Goldberger et al. (2015) showed that the primary barriers to BDM adoption were insufficient knowledge about BDM, high purchase cost, and unpredictable breakdown of BDM in soils. Of the 34 specialty crop growers surveyed, 78% indicated they did not have adequate access to information about BDM, and 68% indicated this was a moderate or serious problem. Additionally, 44% of the growers indicated that lack of knowledge about the effective performance of BDM was a moderate or serious problem. Of the 97 intermediaries (agriculture extension agents, agricultural input suppliers, and crop consultants) who were surveyed, 37% were not familiar and 58% were somewhat familiar with BDM. Similar to growers, 47% of intermediaries indicated that the lack of knowledge about effective BDM performance was the most serious limitation to BDM utilization by growers. A primary concern for all stakeholders was the feedstocks used to make BDM, what they degrade into, and the duration of biodegradation. Other major concerns included a lack of information regarding the economics of using BDM, why BDM is not allowed in certified organic agriculture in the United States, and how the performance of BDM in the field compares with PE mulch. Additional survey work revealed raspberry (*Rubus ideaus*) growers perceive BDMs as risky due to uncertainties associated with in-field durability, soil degradability, and environmental impacts (Madrid et al. 2022). However, all respondents in the Goldberger et al. (2015) study indicated the primary bridges to BDM adoption were increased awareness of reduced waste and environmental benefits among growers and agricultural professionals.

Findings from Goldberger et al. (2015) underscore the need for research and outreach regarding the opportunities provided by BDM relative to nonbiodegradable PE mulch. We expect knowledge and adoption of BDM technology to increase by educating key stakeholders (extension personnel, other agricultural professionals, and producers) about BDM feedstocks, their biodegradation, crop performance, soil health effects, and associated costs and benefits. Further, as key stakeholders gain more knowledge regarding BDM, we expect them to have an increased understanding of the issues associated with BDM approval for organic systems (Miles et al. 2023). Increased adoption of BDM could lead to a decrease in plastic waste generated from agricultural systems.

Agricultural extension serves as a bridge for outreach and education between researchers and growers. Train-the-trainer is a widely practiced educational model in extension that allows for utilization and promotion of social capital in the community, which in turn maximizes the benefit of the training program (Orfaly et al. 2005). Extension representatives identify growers' needs, communicate these to researchers, and then deliver research-based tools and solutions back to target groups. In recent years, extension outreach efforts have been diversified by including electronic mass media such as websites, e-newsletters, video recordings, and multimedia and slide presentations. Electronic mass multimedia has gained popularity compared with printed documents because of their ability to reach a large audience in a timely fashion at low cost (Norton and Alwang 2020). Similarly, the use of webinars has expanded extension programs' sphere of influence, especially for large research projects covering wide geographic regions, due to convenience and affordability (Zoumenou et al. 2015). For example, the northern grapes (*Vitis* sp.) project webinar series conducted over a 4-year period was valued at ~$3.4 million, which included 36 webinars delivered to an audience of 3083 individuals with ~2400 additional views of recorded webinars (Particka et al. 2018). Field days, especially when combined with hands-on demonstrations, can enhance the value of electronic media (Larochelle et al. 2019). In a survey conducted at tree fruit meetings, participants suggested on-farm trials and field demonstrations could speed up adoption of new technologies (Ellis et al. 2010). For more than 100 years, on-farm demonstrations and field days have been used by university extension programs to increase knowledge, awareness, and adoption of agricultural practices and technologies. Further, such extension efforts provide a platform for two-way communication where extension personnel can learn from growers' experience and vice versa. Farmer field days, even as stand-alone events, are found to be a highly effective technology diffusion mechanism (Emerick et al. 2016). The services and outreach tools available through agricultural extension can be implemented to address the knowledge gap and adoption barriers associated with BDM technology.

The objectives of this project were to 1) develop training materials that could be used either as part of a training curriculum or stand-alone presentations for trainers to deliver to their producer clientele, 2) educate and survey extension personnel and other agricultural professionals for self-assessment about BDM and available training materials through trainings and webinars, and 3) educate producers about BDM through hands-on experience and assess the impact by evaluating changes in knowledge by surveying growers regarding BDM performance in strawberry (*Fragaria* ×*ananassa*) production. Information resulting from this project demonstrates how extension programming can develop resources and training

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materials to reach a large audience that shares a common horticultural and environmental challenge.

Materials and methods

Training materials

Thirty-six research and extension publication outputs from two previous US Department of Agriculture Specialty Crop Research Initiative (SCRI) BDM projects from 2009–13 (award no. 2009-51181-05897) and 2014–19 (award no. 2014-51181-22382) were reviewed and transcribed into new extension publications. The 2009–13 SCRI project investigated BDMs in lettuce (*Lactuca sativa*) and tomato (*Solanum lycopersicum*) production under high tunnel and open field environments in three diverse regions of the United States (Miles et al. 2012; Wallace et al. 2012). This project concluded that mulch type and geographic location are primary factors that influence mulch degradation, and abiotic and biotic variables also influence degradation (Li et al. 2014). The 2014–19 SCRI project concluded that BDM can be a viable alternative to PE mulch (Ghimire et al. 2018, 2020). In addition, this project showed that 4 years of continuous use of BDM did not have negative impacts on soil health, and soil moisture and temperature influence the rate of biodegradation (Griffin-LaHue et al. 2022; Sintim et al. 2021). Furthermore, this project identified the bridges and barriers to BDM adoption by growers and intermediaries and further investigated the economic feasibility of agricultural products grown with BDM through the entire supply chain to consumers (Galinato et al. 2020; Goldberger et al. 2015; Velandia et al. 2020).

Knowledge gaps related to BDM were identified based on feedback and questions from stakeholders and growers during presentations and via e-mail, which were leveraged to create a training curriculum. Photos and video recordings collected from the previous projects were cataloged and selected for incorporation into the training curriculum. Additionally, new photos and videos were recorded in growers' fields, BDM experimental plots, and research fields where crops were grown using BDM. Slide presentations and lecture slides with presenter notes, factsheets, videos, and handouts were created and integrated into the curriculum. These materials could also be used as stand-alone training materials depending on the educational needs of the audience. The extension publications were edited and reviewed by collaborators before dissemination to stakeholders and posting on a central university website (Washington State University 2023) where resources could be accessed for free. Horticulture faculty and extension specialists in each state were informed about the training curriculum via e-mail one to three times per year in 2020 and 2021. The website and resources were also promoted in research presentations at academic and stakeholder events. The number of visitors to the website were recorded by state and country.

Professional development trainings

Professional development trainings were conducted at local, regional, national, and international levels to provide agricultural professionals the current, science-based information on BDM and resources for information. A survey was developed and granted exempt from full review by Washington State University's Institutional Review Board (Pullman, WA, USA). The survey quantified changes in knowledge and focused on key topics within each level of training. The survey was distributed at the end of the training, so respondents were able to self-assess their knowledge gain. Trainings at each level are described in the following subsections.

Local level. A local professional development training was conducted in person in Watsonville, CA, USA on 4 Feb 2020. The topics covered in the training were 1) introduction to BDM, 2) application and use of BDM, 3) deterioration and degradation of BDM, 4) soil sampling for visible plastic fragments, and 5) economics of using BDM. The participants were asked to take a survey to evaluate their level of knowledge before and after the training on a 1 to 5 scale where 1 represented "not at all" and 5 represented "very high" (Fig. 1). The survey also included open-ended questions to assess information gaps regarding BDM.

Regional level. A regional professional development training was conducted virtually via webinar for agriculture professionals in the northeastern United States on 18 Nov 2020. The topics covered in the training were 1) introduction to BDM, 2) application and use of BDM, 3) deterioration and degradation of BDM, 4) impact of BDM on soil health and quality, and 5) economics of using BDM. The participants were asked to take a posttraining survey to assess knowledge gain. The survey was conducted using the polling feature in Zoom (Zoom Video Communications, San Jose, CA, USA), and the responses were collected anonymously.

National level. A national professional development training was conducted virtually via webinar for members of the American Society for Horticultural Science on 27 Jul 2020. The topics covered in the training were 1) introduction to BDM, 2) application and use of BDM, and 3) deterioration and degradation of BDM. The participants were asked to take a posttraining survey to assess knowledge gain. The survey was conducted using the polling feature in Zoom, and the responses were collected anonymously.

International level. An international professional development training was conducted as a virtual webinar on 1 Mar 2022 to share research results from BDM studies and firsthand information from growers using BDM.

Growers' training

In Jun 2020, a BDM application field day was held in Watsonville, CA, USA, which was attended by 15 strawberry growers and crop consultants. At the event, BDMs were defined, and a demonstration was carried out to machine-lay BDMs.

After the training, five strawberry growers including one certified organic grower volunteered to host on-farm demonstrations of four BDM products on their farms (Table 1). The trials took place in five US towns in California's Central Coast: Corralitos, Watsonville, Moss Landing, Castroville, and Royal Oaks. Each grower applied BDMs in unreplicated plots adjacent to their standard PE mulch or totally impermeable film (TIF) on raised beds. BDM application occurred between Sep and Dec 2020, and strawberries were planted between Oct and Jan 2021. The trials allowed extension personnel and growers to observe the performance of BDM in a commercial setting and within different regional microclimates.

Early-, midseason, and late-season (post-BDM incorporation) interviews were carried out with the five key

Evaluation of Soil-Biodegradable Mulch Workshop

1. Please provide a response to each question based on your knowledge of polyethylene (PE) and soil-biodegradable plastic mulches (BDM) before and after the workshop:

BEFORE the workshop						AFTER the workshop				
Not at all				Very		Not at all				Very
1	2	3	4	5		1	2	3	4	5
○	○	○	○	○	Limitations to PE mulch disposal	○	○	○	○	○
○	○	○	○	○	Feedstocks used to make BDM	○	○	○	○	○
○	○	○	○	○	Deterioration & degradation of BDM	○	○	○	○	○
○	○	○	○	○	Biodegradability standards	○	○	○	○	○
○	○	○	○	○	Field application of BDM	○	○	○	○	○
○	○	○	○	○	Weed control with BDM	○	○	○	○	○
○	○	○	○	○	BDM lack of suitability for fumigation	○	○	○	○	○
○	○	○	○	○	BDM use in organic production	○	○	○	○	○
○	○	○	○	○	Crop yield with BDM	○	○	○	○	○
○	○	○	○	○	Sampling soil for PE mulch and BDM	○	○	○	○	○
○	○	○	○	○	Cost of using PE mulch vs BDM	○	○	○	○	○

2. Have you used BDM in your operation (circle response)? Yes No
If yes, on acres for crops:____________________

3. Given the information you gained during the workshop, what are your primary concerns or questions regarding BDM:

4. Did you learn something today that will help you with your business (circle one)? Yes No Maybe
If yes or maybe, please give an example:

5. Were there any topics that are very important to you not covered at this workshop (circle one)?
Yes No Maybe If yes or maybe, please list them:

Thank you for completing the workshop evaluation

Fig. 1. Survey questionnaire used for evaluation at a local-level professional development training in soil-biodegradable plastic mulch for strawberry growers and crop consultants in Watsonville, CA, USA, on 4 Feb 2020.

grower participants, and mulch performance was assessed every month until the end of the season in collaboration with extension specialists in California, USA. An early season survey was carried out using an online survey software (Qualtrics XM; Qualtrics, Provo, UT, USA) in May 2021 to assess the familiarity of growers with BDM and their expectations of BDM performance in their fields. Familiarity of grower participants to different aspects of BDM was measured on a 5-point scale: not familiar, slightly familiar, moderately familiar, very familiar, and extremely familiar. Similarly, the likelihood of BDM to meet their expectations was measured on a 5-point scale: not likely, slightly likely, moderately likely, very likely, and extremely likely. Midseason and late-season surveys were carried out in person in Aug and Dec 2021, respectively, to evaluate BDM performance in the field.

We also cohosted a farmers' field day in Salinas Valley, CA, USA, on 17 Aug 2021 in collaboration with the California Marine Sanctuary Foundation, Monterey, CA, USA; Monterey Bay National Marine Sanctuary Foundation, Santa Cruz, CA, USA; University of California Agriculture and Natural Resources, Davis, CA, USA; and California Polytechnic State University, San Luis Obispo, CA, USA. The event included several presentations by faculty and graduate students and covered the following topics: 1) introduction to BDMs and its constituents, 2) plastics in agricultural soils: distribution and implications, 3) plastics in soils and its biological consequences, 4) economics of BDMs, and 5) measurements for BDM performance. After these presentations, there was a farmer-led panel discussion on their experiences with BDMs and tours that showcased the BDM plots.

Table 1. Mulch type and thickness used by strawberry (*Fragaria ×ananassa*) grower participants for on-farm demonstration of soil-biodegradable plastic mulch in Salinas Valley, CA, USA, in 2021.

Identification	Biodegradable feedstocks used[i]	Thickness (mils)[ii]
Grower 1	Ecovio[ii]	1.1, 1.3, 1.6
	Mater-Bi[iii]	2.0
Grower 2	Ecovio	1.1, 1.6
Grower 3	Mater-Bi	2.0
Grower 4	Ecovio	1.6
Grower 5	Ecovio	1.1, 1.3, 1.6
	Mater-Bi	2.0

[i] Key ingredients for Ecovio (BASF, Ludwigshafen, Germany) are polylactic acid (PLA) and polybutylene adipate terephthalate (PBAT); key ingredients for Mater-Bi (Novamont, Novara, Italy) are starch and PBAT.
[ii] 1 mil = 0.0254 mm.

Data analysis

The data regarding the participants' knowledge change from the trainings were tabulated, means were generated for comparison purposes, and percentages are reported. No further statistical analyses were conducted due to the nature and design of the evaluations. In addition, descriptive data were recorded where quantitative assessments were not feasible.

Results and discussion

Training materials

Altogether, 45 training materials were developed that included 11 slide presentations, 5 lecture slides, 10 fact sheets, and 3 videos (Fig. 2). Presenter notes that included a list of references were developed for each slide presentation and lecture slide set, to

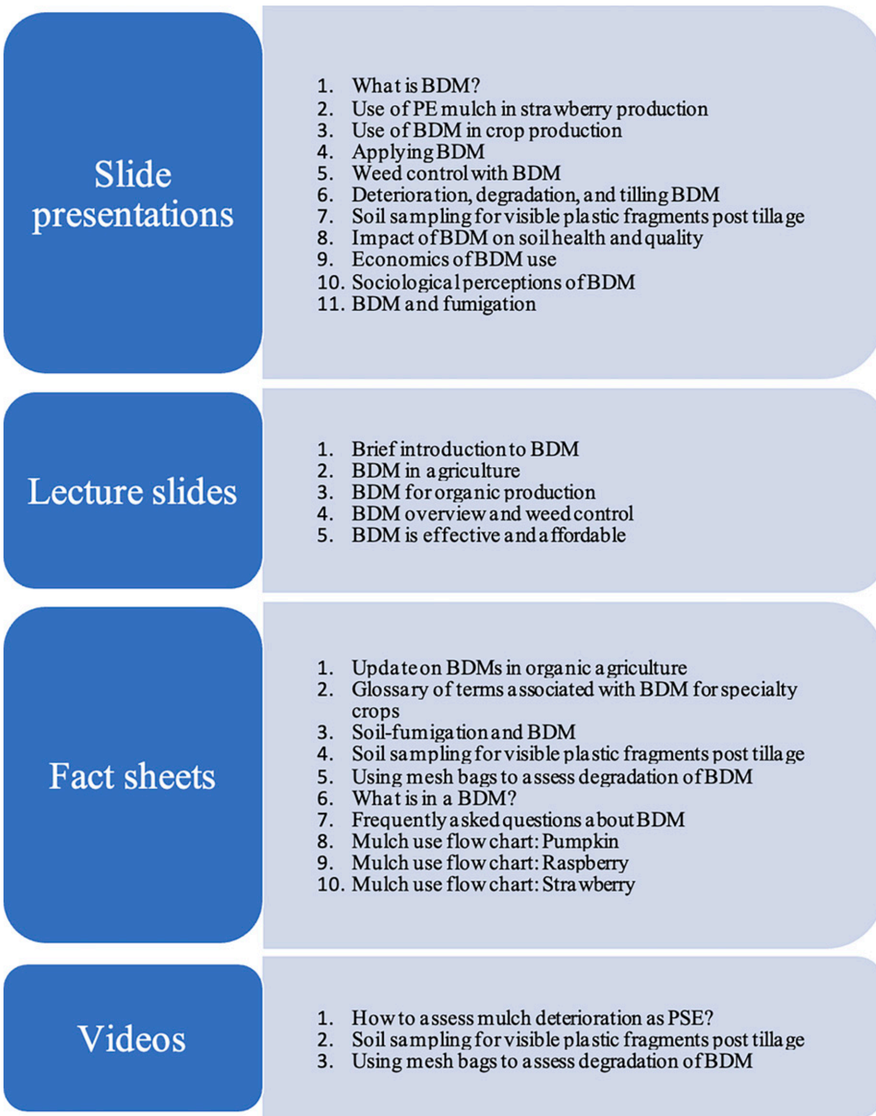

Fig. 2. List of training materials in soil-biodegradable plastic mulch (BDM) developed to fill information gaps and uploaded to the project webpage (Washington State University 2023); PSE = percent soil exposure; pumpkin (*Cucurbita pepo*), raspberry (*Rubus ideaus*), strawberry (*Fragaria ×ananassa*).

help presenters gain in-depth knowledge on the subjects. All the training materials were uploaded to the website in Jul 2020 to facilitate easy and free access to stakeholders. In addition, the Twitter handle "@Mulch_Matters" (Twitter, Inc., San Francisco, CA, USA) was started in Aug 2021 to update stakeholders and the general public as the training materials were being made available. As of 31 Dec 2022, 6641 visits to the website from 78 countries were recorded. Of these visits, 63% were from the United States, 3% were from Canada, and the remainder was from other countries that each had less than 1% of the visits. Further, 42% of the visitors were from Washington State, 5% from California, 2% from Connecticut, and the remaining 51% were from other regions of the United States and other countries. This distribution of website visitors demonstrates the training materials developed in this project reached stakeholders in the United States as well as internationally. As of 25 May 2023, we have 55 followers on Twitter from the agricultural, mulch manufacturing, and recycling industries. Furthermore, we have had a total of 35 tweets since 2021.

Professional development trainings

In the local professional development training conducted in Watsonville, CA, USA, 28 participants attended, comprising 29% organizational representatives, 21% agricultural industry representatives, 21% growers, 14% educators, and 14% government agents. The greatest change of knowledge among participants was observed for "BDM use in organic production" (60%), and the least change of knowledge was observed for "limitations to PE mulch disposal" (19%) due to high familiarity of participants with this topic before the training (Fig. 3). Limitations to PE disposal include high cost for landfill disposal or nonacceptance of PE mulch by some counties for disposal, nonrecyclability of used PE mulch, and incomplete removal of PE mulch from the field due to breakage.

In the regional professional development training conducted for agriculture professionals in the northeastern United States, 58 participants attended, comprising 55% extension specialists, 20% teaching/research faculty, 3% industry representatives, 3% others, and 19% did not respond. Of the participants, 23% to 35% responded that they learned "a lot" and 35% to 51% that they learned "some new information" regarding BDM from the webinar (Fig. 4). The majority of participants (51%) indicated that they were "very likely" to use the information and resources learned at the training and 26% of participants were "somewhat likely" to do so.

In the national professional development training conducted for members of American Society for Horticultural Science, 30 participants attended, comprising 38% teaching/research faculty, 24% extension specialists, 19% graduate students, and 19% others. Of the participants, 48% responded that they learned "a lot" and another 48% that they learned "some new information" on BDM from the training (Fig. 5). When the participants were asked about the likelihood of using information and resources learned at the training program in the future, 57% indicated they would be "very likely" and the rest indicated "somewhat likely" to do so. Interestingly, 95% of the attendees expressed an interest in participating in future BDM trainings.

The international professional development training was attended by 74 participants. Four growers from across the United States and Italy who have been using BDM for 1 to 25 years in vegetables and strawberry participated as panelists to share their experience

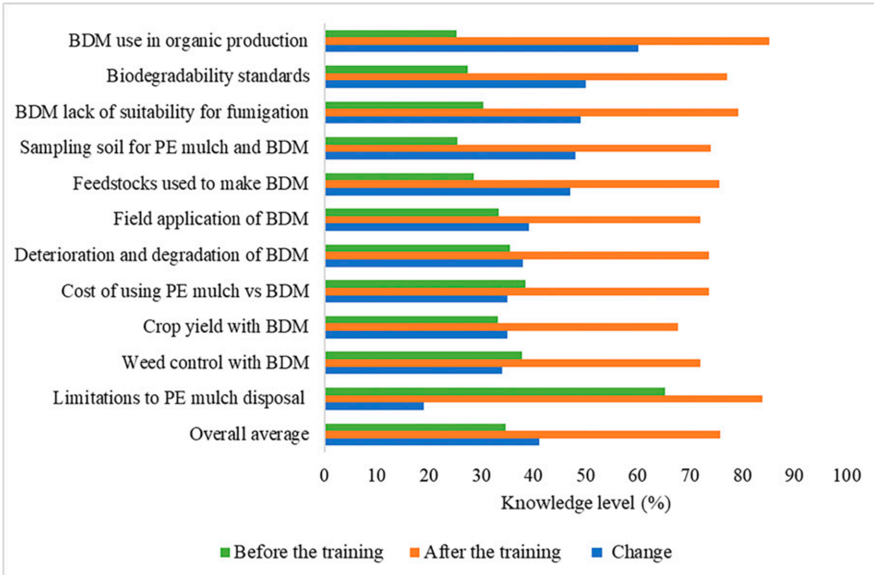

Fig. 3. Participants' (N = 28) self-assessed level of knowledge before and after the professional development training on soil-biodegradable plastic mulch (BDM), where 0 = no knowledge and 100 = complete knowledge, and change, in Watsonville, CA, USA, on 4 Feb 2020; PE = polyethylene mulch.

with BDM. The common reason for switching to BDM shared by all growers on the panel was labor constraints for PE mulch removal at the end of the growing season. The key experiences shared by the grower panel is summarized next.

For the past 20 years, each spring, BDM was almost completely (visibly) gone after tilling it in the previous fall. Immediately after tillage, BDM fragments were a quarter the size of initial fragments (it is important to note that the degradation process includes the reduction in size from fragments to microplastics to nanoplastics, and finally to carbon dioxide and microbial biomass) BDM degradation is weather-dependent. BDM biodegrades faster in "healthier" soil. The purchase cost for BDM is ~$180/acre higher compared with PE mulch, but the cost of labor and materials for retrieving PE mulch plus the cost for transportation and disposal at the end of the season is more than $180/acre. A fundamental reason for switching to BDM was to save labor and improve working conditions; picking up PE fragments during the wet and cold season between October and November was not favored by employees working on growers' farms. Use of BDM allows timely planting of cover crops in the autumn. Customers are happy to see less plastics used on the farm.

Multilayered outreach efforts from local to international levels can help extension personnel and other agricultural service providers learn from one another's experiences and use those lessons to address local, regional, and global challenges. There are some challenges to the adoption of BDM that extend to the national and international level, such as higher purchase cost and knowledge gaps. Additionally, there are barriers that are specific to regions, such as concerns of marine debris in California and Connecticut, USA, which may not be a concern in noncoastal areas. Having a mix of international, state, and regional outreach efforts helps stakeholders and extension personnel have a better understanding of BDMs and identify actions to overcome relevant barriers for their location.

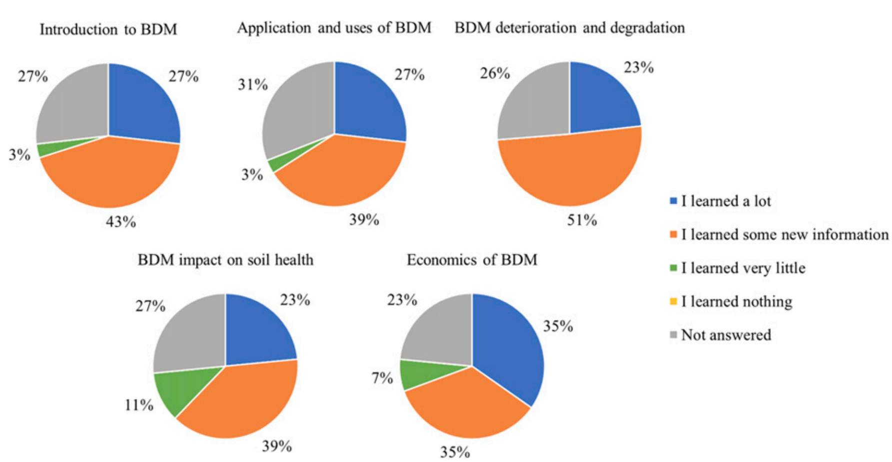

Fig. 4. Responses of participants (N = 58) after the professional development training in soil-biodegradable plastic mulch (BDM) conducted virtually for agriculture professionals in the northeastern USA on 18 Nov 2020.

Growers' training

The field day demonstrated that BDM application is very similar to PE or TIF mulch application. Of note, it was demonstrated that the same mulch-laying equipment can be used to apply BDM, and application time was equivalent to PE and TIF after minor initial adjustments to mulch tension. These adjustments were described by the farmers and attending consultants to be normal for any new mulch application regardless of the type of plastics. Growers and crop consultants were also able to touch, feel, and compare BDM to PE and TIF. Many expressed surprise at how quickly and easily BDM was applied as well as how similar BDM was to PE in this respect. All participants noted that the black color of the BDM was not desirable, as strawberry growers in Watsonville, CA, USA, typically prefer a dark-matte green film for reasons of aesthetics, increased film transparency relative to black film, and subsequent effects on soil warming. Despite this color preference, five growers subsequently volunteered to trial BDM on their own farm.

On-farm demonstration

Early-season survey. Only two of the five growers who hosted on-farm trials responded to the Qualtrics survey. The farm sizes of these two strawberry grower respondents were 26 and 32.5 acres, respectively. Both respondents indicated low familiarity

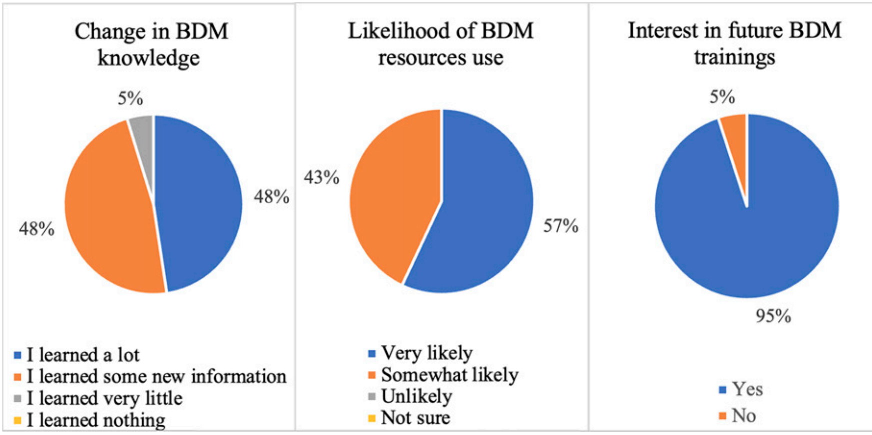

Fig. 5. Responses of American Society for Horticultural Science members (N = 30) after the professional development training in soil-biodegradable plastic mulch (BDM) conducted on 27 Jul 2020.

Fig. 6. Strawberry (*Fragaria* ×*ananassa*) growers in Salinas Valley, CA, USA, present to agricultural stakeholders during a field day in soil-biodegradable plastic mulch for strawberry production on 17 Aug 2021.

with BDM feedstocks, commercially available BDM products, BDM biodegradation in the soil, and standards for BDM. Moreover, the respondents perceived BDM as very or extremely likely to perform comparably to PE mulch and TIF in the field and produce similar fruit quality. The participants expressed the preference to have green-colored mulch.

Mid-season survey. The mid-season survey included responses from all five grower on-farm trial hosts. The respondents had observed surface deterioration on BDM beds that started 5 to 6 months after mulch application. Soil moisture and humidity, placement of bags of soil on top of the mulch bed (a standard practice at one operation to reduce damage from wind), and use of mechanical equipment during the growing season were the primary causes of BDM deterioration in the field. Approximately 4 months after transplanting, weed growth was first observed in bed areas where BDM had started to deteriorate, but weeds were not substantial. The respondents indicated that BDM had comparable weed control and also fruit yield and quality to PE mulch and TIF based on their visual observations. Respondents expressed their concern regarding the high purchase cost of BDM. Meanwhile, the organic grower respondent's concern was the added cost of BDM fragment removal in addition to high purchase cost.

Late-season survey. The late-season survey had respondents from three of the five grower on-farm trial hosts. All three respondents stated that overall, they observed no difference between the PE mulch and the BDM. By the end of the season, all three respondents stated that weed control and fruit yield provided by the BDM and PE mulch were similar. Concerns expressed by growers included 1) the slow rate of biodegradation after tillage, 2) potential impacts of BDM on soil biological activity, and 3) inability to use the current commercially available BDM in organic production. Leaving a field with plastic fragments, even if soil-biodegradable, represents both an aesthetic and a food safety problem. To illustrate the issue in Monterey Bay, CA, USA, the majority of strawberry fields are rotated with vegetable crops, and some of these vegetable crops are packaged in the field; any plastic contamination in the crop packaging process would result in food safety concerns and product rejection. To overcome this obstacle, growers can opt to rotate with a crop that is not impacted by the BDM residue, such as Brussels sprouts (*Brassica oleracea* var. *gemmifera*). Plastic fragments left in agricultural fields can further degrade and create a transitional microbial hotspot (McKay et al. 2022). However, it is unknown how these distinct biological hotspots affect commercial agricultural systems. Additionally, commercially available BDMs do not meet the National Organic Program requirement that BDMs be made of 100% biobased content. The National Organic Standards Board (US Department of Agriculture, Agricultural Marketing Service 2021) is considering an annotation change to reduce the biobased content requirement to 80%, but even with this adjustment, no commercially available BDMs currently meet the requirements for use in certified organic production. In juxtaposition, growers stated that BDM use would result in less plastic going into the landfill and would reduce labor costs associated with post-use mulch management. The feedback provided by the grower on-farm trial hosts provides extension personnel a realistic look at regional concerns and benefits that may arise from commercial agricultural stakeholders.

Farmers' field day. Approximately 40 participants attended the event. The participants observed similar weed control and fruit yield for BDM and nonbiodegradable plastic mulch (e.g., PE and TIF) in the BDM demonstration field. After 10 months in the field, the BDMs had minimal deterioration. Four of the five growers demonstrating BDM on their farms were available to attend the field day and shared their experiences to facilitate farmer-to-farmer information sharing (Fig. 6). The farmer-to-famer extension approach dates backs at least to the 1950s (Selener et al. 1997); such an approach is widespread and considered effective among extension educators. At the field day, on-farm hosts highlighted the importance of exploring alternatives to nonbiodegradable plastic mulch (PE and TIF) and expressed strong motivation to reduce plastic use in their fields. Side-by-side trial applications of BDM allowed for direct comparison with PE and TIF mulch. Further, field-day participants were able to observe that plant performance with BDM was the same as with standard PE or TIF mulch. The on-farm hosts also indicated that they plan to continue trialing or supporting experimentation of BDM. Concerns were also highlighted; these included uncertainties regarding the residence time of degrading fragments in soil, particularly if a leafy green crop rotation follows as the degrading fragments could become a harvest contaminant. In addition, one grower emphasized the importance of pursuing approval for BDM use in organic agriculture. The observations and concerns expressed in the field day by the participating growers and the agricultural stakeholders in attendance were similar to those collected in the grower surveys.

Conclusions

The training materials developed from this study and their free and open accessibility will contribute to filling information gaps regarding BDM. For example, the concerns raised by on-farm trial participants regarding the high purchase cost of BDM, the slow rate of biodegradation after tillage, potential impacts of BDM on soil biological activity, and inability to use the current commercially available BDM in organic production are all addressed in the training materials. The concern that growers raised regarding the negative aesthetics of BDM fragments in the field could be addressed by raising awareness that fragments are an essential step in the degradation process. The grower concern regarding the food safety risk of BDM fragments can be addressed by crop rotation. Through evaluation surveys throughout this project, we documented notable changes in the awareness and knowledge among extension and agricultural agency personnel regarding BDMs, including application of BDM for crop production, BDM deterioration and degradation, BDM impact on soil health, BDM use in organic production, and costs and benefits of BDM. The promising results from the on-farm BDM demonstrations shared at field days in California, USA, have raised awareness among growers about BDM and opened up opportunities for additional large-scale field trials and demonstrations at the grower level. On the basis of our experience, on-farm demonstration and field days made a positive impact on the perception of growers toward BDM by providing hands-on experience. The on-farm BDM demonstrations involving growers were not replicated in this study, and future research studies should engage growers in replicated BDM on-farm trials to draw stronger conclusions. The outreach activities included in this project were effective for educating agricultural professionals and extension personnel about the limited end-of-life management options for PE mulch and the role of BDM to overcome mulch disposal challenges while maintaining crop productivity.

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