HortScience 59(10):1524–1533. 2024. https://doi.org/10.21273/HORTSCI18029-24

Alternative and Emerging Mulch Technologies for Organic and Sustainable Agriculture in the United States: A Review

Nataliya Shcherbatyuk
Department of Viticulture and Enology, Washington State University, Irrigated Agriculture Research and Extension Center, 24106 N. Bunn Road, Prosser, WA 99350, USA

Sam E. Wortman
Department of Agronomy and Horticulture, University of Nebraska - Lincoln, 362F Plant Sciences Hall, Lincoln, NE 68583, USA

Dakota McFadden and Ben Weiss
Department of Horticulture, Washington State University, Northwestern Washington Research and Extension Center, 16650 State Route 536, Mount Vernon, WA 98273, USA

Sharon Weyers
US Department of Agriculture, Agricultural Research Service, Soil Management Research, 803 Iowa Avenue, Morris, MN 56267, USA

Waqas Ahmad
Department of Plant Sciences, North Dakota State University, Loftsgard 474C, Fargo, ND 58102, USA

Dilpreet S. Bajwa
Mechanical & Industrial Engineering Department, Montana State University Roberts Hall 220, Bozeman, MT 59717, USA

Suzette P. Galinato
Agriculture and Natural Resources, Washington State University, 117 Hulbert Hall, Pullman, WA 99164, USA

Alice Formiga
Department of Horticulture, Oregon State University, 2750 SW Campus Way, Corvallis, OR 97331, USA

Greta Gramig
Department of Plant Sciences, North Dakota State University, Loftsgard 474C, Fargo, ND 58102, USA

Lisa Wasko DeVetter
Department of Horticulture, Washington State University, Northwestern Washington Research and Extension Center, 16650 State Route 536, Mount Vernon, WA 98273, USA

Keywords. biobased, certified organic, plastic mulch, soil-biodegradable mulch, sprayable mulch, tackifiers

Abstract. **Plastic mulches made from nonbiodegradable polymers (e.g., polyethylene) provide an essential service in commercial horticultural production systems by enhancing crop productivity through weed suppression, soil moisture conservation, and moderating soil and canopy temperature conditions. Plastic mulches are particularly important in organic agriculture because weed management options are limited. Nevertheless, there is increasing concern about addressing the negative environmental impacts of plastic mulch waste. Soil-biodegradable plastic mulch (BDM) films that are designed to biodegrade in soils after incorporation are promising alternatives to nonbiodegradable plastic mulch. However, although the US organic standards technically permit the use of BDM films, no commercially available products meet National Organic Program (NOP) requirements for 100% biobased content and 90% degradation after 2 years following soil incorporation (7 Code of Federal Regulations, section 205.2). Other concerns about biodegradable film mulches include high perceived cost, esthetics, and uncertainties regarding the impacts of soil incorporation. New mulch technologies have emerged to diversify sustainable mulch options and overcome barriers associated with BDM film use in organic production. The objective of this study was to provide an overview of alternative and emerging mulch technologies, with an emphasis on biodegradable mulches, including water-based sprayable mulches such as hydromulch and foam mulch, and biobased agrotextiles. Information about how these mulch technologies contribute to organic and sustainable agriculture is provided, along with definitions, opportunities, challenges, and recommended areas for future research.**

Mulches are integral components of sustainable horticultural crop production because of their ability to suppress weeds, conserve soil moisture, modify soil temperature, and enhance crop productivity and quality (Gheshm and Brown 2020; Iriany et al. 2018; Kader et al. 2017; Li et al. 2014; Nwosisi et al. 2019; Sadek et al. 2019; Wortman et al. 2016). Mulches are particularly important in organic production systems because weed management options are limited. However, improper implementation or the use of unsuitable mulch materials for a particular application or climatic region can result in negative production and environmental outcomes. Most mulches used in commercial systems (Fig. 1) are extruded as films and consist of synthetic feedstocks, such as nonbiodegradable polyethylene (PE). Soil-biodegradable plastic mulch (BDM) films are also available as an alternative to PE mulch and are typically made with a blend of fossil fuel-based and biobased feedstocks (Miles et al. 2017). Mulches can also be made with natural materials, including crop residues, wood chips, gravel, and cover crops that may be allowed to grow (i.e., living mulches) or ended with a roller-crimper or other implement (Haapala et al. 2014; Leary and DeFrank 2000; Testani et al. 2019).

Standards governing certified organic production in the US regulate the use of synthetic

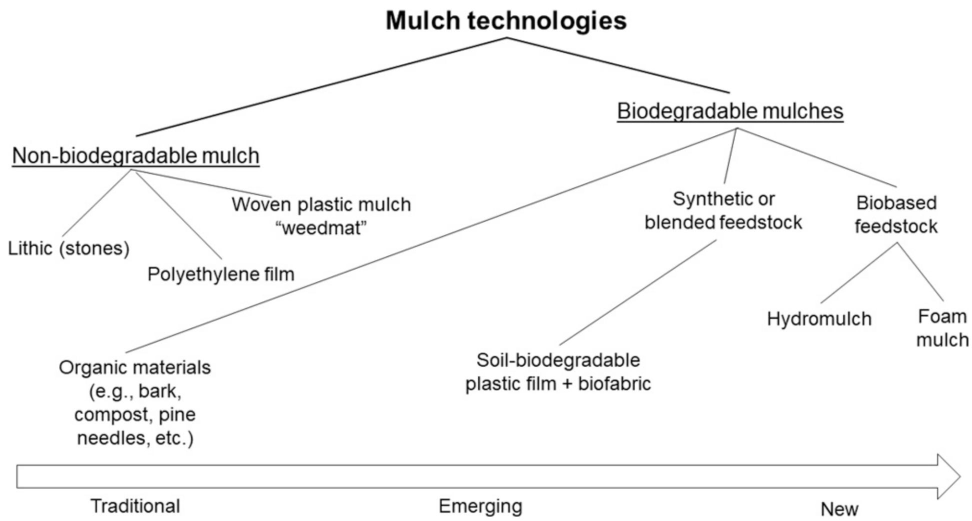

Fig. 1. Mulch includes nonsoil biodegradable and biodegradable mulches, which may be derived from synthetic or natural materials. Emerging and new mulch technologies may be made with synthetic, biobased, or a combination of synthetic and biobased ingredients that have the potential to eliminate long-term plastic waste generation.

mulch options such as PE mulch and BDMs because of their potential negative impacts on the environment. Currently, PE mulch is allowed in certified organic production, but it must be completely removed from the field following the growing season if deployed in certified organic systems because the mulch is nonbiodegradable (7 CFR 205.601; US Department of Agriculture 2014b). Complete mulch removal can be difficult to achieve and may lead to residual mulch fragments becoming soil pollutants (Briassoulis et al. 2010; Cole et al. 2011; Shitong et al. 2022). Moreover, end-of-life management of PE mulch entails stockpiling, burning, and landfilling, which can also contribute to soil and environmental pollution (Goldberger et al. 2019; Kasirajan and Ngouajio 2012; Madrid et al. 2022; Moore and Wszelaki 2016, 2019). BDMs are designed to function similarly to PE mulch but presumably eliminate plastic mulch pollution by biodegrading completely when incorporated into agricultural soils (Tofanelli and Wortman 2020). The US National Organic Program mandates that, for use in organic agriculture, BDMs must be 100% biobased [determined by the American Society for Testing and Materials (ASTM) D6866]; however, no commercially available BDM films meet this criterion (7 CFR 205.2; US Department of Agriculture 2014a). In Oct 2021, a rule change was proposed to alter the minimum allowable biobased content for BDM to 80%, but this change was not approved at the time of this publication. Additional requirements for BDM use in organic agriculture include meeting compostability specifications (following ASTM D6400, ASTM D6868, EN 13432, EN 14995, or ISO 17088), achieving at least 90% biodegradation in soil within 2 years (based on ISO 17556 or ASTM D5988 standards), and production without organisms or feedstocks derived from excluded methods (Miles et al. 2023).

New mulch technologies have emerged to diversify sustainable mulch options and overcome barriers associated with BDM use in certified organic production (Fig. 1). Water-based, sprayable "hydromulches" made from polysaccharides or hydrolyzed proteins are a possible alternative to plastic mulches. Foam mulches, which create foam after their application, are another water-based sprayable mulch alternative. These alternative mulch technologies can be made with biobased ingredients and can meet requirements for organic agriculture; however, they warrant further investigation to assess their viability in commercial horticultural production systems. Furthermore, these water-based mulches can be made with biodegradable and recycled or waste-stream materials that alleviate concerns about plastic pollution and promote more closed-loop production systems. Agrotextiles made from biobased ingredients (biofabrics) such as polylactic acid are another promising mulch technology deserving of more research focus and outreach.

Information about alternative mulch technologies is dispersed among the scientific literature, and no comprehensive review has compared alternative mulch technologies that could play a role in organic and sustainable horticultural production systems. Therefore, the objective of this article was to provide an overview of alternative and emerging mulch technologies with an emphasis on biodegradable mulches, including water-based sprayable mulches such as hydromulches and foam mulches, as well as biobased agrotextiles. Insights about how these mulch technologies contribute to organic and sustainable agriculture are provided, along with definitions, opportunities, challenges, and recommended areas for future research. It is important to note that certified organic producers should be aware of potential risks when using any pest control product within their operations. Therefore, general recommendations include the following: ensure that the product or material is legal to use for the crop and pest as well as in the location where it will be applied; understand any safety precautions and application restrictions for the product or material; and make sure any brand name products are listed in the Organic System Plan and approved by the operation's specific US Department of Agriculture (USDA)-approved certifier. All products must be approved by a certifier, including any products or materials being considered for managing unanticipated pest problems.

Soil-Biodegradable Plastic Mulches

All BDM films are designed to biodegrade in the soil after tillage via metabolism

Received for publication 19 Jun 2024. Accepted for publication 8 Aug 2024.
Published online 18 Sep 2024.
This work was supported by the Organic Research and Extension Initiative Award #2021-51300-34909 and Specialty Crop Research Initiative Award #2022-51181-38325 from the USDA National Institute of Food and Agriculture. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the US Department of Agriculture. Additional support was provided by the USDA NIFA Hatch Project 1014527. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the USDA or project team. USDA is an equal opportunity employer and provider. Additionally, we extend our sincere gratitude to Pierre Sarazin for his invaluable contributions and meticulous review of this manuscript. His insightful feedback and thoughtful suggestions have greatly enhanced the quality and clarity of our work.
Data are stored and available in the following repository: https://library.ndsu.edu/ir/handle/10365/33038.
Sam E. Wortman has disclosed a financial interest in Sage Eco-Innovations, LLC, a company that develops, manufactures, and sells biobased mulch products. In accordance with its Conflict of Interest (COI) Policy, the University of Nebraska–Lincoln COI in Research Committee has determined that this must be disclosed.
D.M. is a former MS student at Washington State University.
L.W.D. and G.G. are the corresponding authors. E-mails: lisa.devetter@wsu.edu and gramig@ndsu.edu.

by native soil microorganisms and have been developed as a potential alternative to nondegradable plastic film mulches like PE mulch. Meta-analyses indicated that despite lower weed suppression, crop yields are not different across a diversity of specialty crops when BDMs are compared with PE mulch (Tofanelli and Wortman 2020). Biodegradation of BDMs may take several years, depending on soil and climactic conditions unique to a site or region, and seasonal and specific polymer chemistry factors also influence biodegradation rates (Brodhagen et al. 2017; Griffin-LaHue et al. 2022; Li et al. 2014). Commercially available BDMs are produced using a blend of biobased and fossil fuel-derived materials. Currently, the amount of biobased material in these mulches is less than the minimum required for use in certified organic agriculture in the US (7 CFR 205.601, 7 CFR 205.2; Brodhagen et al. 2015; DeVetter et al. 2021; Madrid et al. 2022, Miles et al. 2023; US Department of Agriculture 2014a, 2014b; Zhang et al. 2020). However, BDMs are allowed in organic production in some countries in Europe. For instance, BDMs were allowed in France under NFU 52-001 and in Italy under UNI 11495 for an extended period without specific requirements regarding biobased material content (Bettas Ardisson et al. 2014; Kyrikou and Briassoulis 2007). In Jan 2018, the European Committee for Standardization (CEN) introduced the first international standard concerning BDM use, which is known as European Standard EN 17033. Current BDM regulations in Europe do not mandate specific biobased content (Hayes and Flury 2018). In Canada, BDMs were initially approved for organic agriculture without specific biobased criteria; however, in 2016, the approval was adjusted by the Canadian Organic Program and required products to be 100% biobased (Organic Federation of Canada 2018).

BDM use in organic agriculture is controversial. Although high biobased content is important for reducing the use of nonrenewable resources, increased biobased content is not positively or negatively correlated with the extent or speed of in-field degradation. Degrading BDM fragments that include nonbiobased or biobased ingredients could theoretically impose long-term soil health consequences (Tofanelli and Wortman 2020), although no current research data have confirmed this (Sintim et al. 2019, 2020). Moreover, the unknown fate and residence time of BDM breakdown products and the subsequent consequences these products pose for ecosystem health, as perceived by growers and stakeholders, have raised concerns (Wortman et al. 2022). To reduce possible environmental consequences of BDM use in agriculture, biodegradability and composting guidelines such as ASTM D6400 and EN 17033 are in place. Although these guidelines are highly relevant, material performance in these standardized tests may not translate to field performance across a range of soil and environmental conditions. Biodegradable feedstock polymers used to manufacture BDMs comprise ester bonds or polysaccharides that are broken down by microbial hydrolysis (Brodhagen et al. 2015). These feedstock polymers should, hypothetically, be entirely catabolized by soil microorganisms and converted to microbial biomass, CO_2, and water (Bandopadhyay et al. 2018). However, finished mulch films made with biodegradable feedstock ingredients may not biodegrade like raw feedstocks. A finished BDM film contains 75% to 95% polymeric feedstock, with the remaining ingredients being additives and minor components (i.e., lubricants, fillers, and antioxidants) that could influence soil biodegradation in the field (DeVetter et al. 2021).

In some studies, BDMs have shown little in-soil biodegradation (only 9%) over an 18-month period (Zhang et al. 2020) and may take up to 21 to 58 months to attain 90% degradation in certain soil types and climates (Griffin-LaHue et al. 2022). Griffin-LaHue et al. (2022) demonstrated that BDMs in the maritime climate of Washington State accumulated fewer cumulative degree days under field conditions relative to the laboratory conditions specified in BDM standards (EN 17033 2018; Hayes and Flury 2018). These findings demonstrate that mulch films that reach 90% biodegradation within 2 years in laboratory conditions may not perform similarly when used in the field. Field test protocols should be developed to estimate the time for realistic in-field degradation across a range of production scenarios (Griffin-LaHue et al. 2022).

Additional challenges associated with BDMs include costs, difficulty sourcing BDMs, and possible differences in horticultural benefits compared with PE mulch (Tofanelli and Wortman 2020). Farmer perception studies of BDMs also identified several barriers to adoption, including poor on-farm esthetic qualities, higher initial costs, questionable durability, and unknown breakdown times (Dentzman and Goldberger 2020; Goldberger et al. 2015, 2019). Surveys and focus groups found that 45% of participating growers were skeptical that BDMs would fully break down after field use, and 47% considered the higher cost of BDMs a moderate to serious challenge (Goldberger et al. 2015). Additional work by Dentzman and Goldberger (2020) found that the practice of keeping farm grounds "clean and neat" is a sign of cultural capital. BDM breakdown esthetics were associated with "messy, unkempt, and bad" farming practices, which, as a visual cue, indicate that a grower lacks the skill or motivation to keep the farm looking nice and producing well. However, in recent years, prices of BDMs have decreased, becoming only slightly higher than that of PE mulch, and economic studies often indicate that BDMs provide significant cost-savings when factoring in costs of removal and disposal (Galinato et al. 2020; Velandia et al. 2018, 2019). Additionally, thicker and more durable BDMs designed for longer-season crops have become available. Overall, BDMs are a promising mulch alternative to nonbiodegradable mulches, but their future approval for use in US organic production systems remains uncertain. Alternative biodegradable mulch technologies are necessary to replace PE mulch and provide the organic industry with viable alternatives that meet both sustainability and production requirements for commercial operations.

Hydromulches

Hydromulch (also known as "hydramulch") consists of a water-applied slurry (Fig. 2) made from polysaccharide feedstocks and sometimes a tackifier (i.e., glue) that is sprayed onto the soil surface before transplanting. Hydromulches can be applied around existing trees or shrubs to prevent erosion, suppress weed emergence, and foster revegetation (Faucette et al. 2006; Hansford 1981). Despite the widespread use of hydromulches for restoration and erosion-control projects such as hydroseeding, documented research of their use in horticultural production systems is limited and likely varies given nonuniformity in hydromulch material composition and application rates (Faucette et al. 2006; Lopéz-Marin et al. 2021; Mas et al. 2021; Romero-Muñoz et al. 2024). Hydromulch presents an appealing option because of its perceived ease of application. It is sprayable and can be formulated using biobased and other organic-approved ingredients, making it potentially certifiable for US organic production. Polysaccharide fibers are typically derived from cellulose, and the resultant hydromulch creates a semipermeable barrier over soil. If paper is used as a cellulosic fiber source, then that paper must be made with 100% recycled content; however, if the paper contains glossy or colored inks, then it will not be allowed for use in certified organic agriculture (National Organic Program rules § 205.601 and § 205.2 respectively; National Organic Program 2022).

Research that investigated hydromulch use in specialty crop systems has been promising and has primarily used cellulose as the fiber source (Anderson et al. 1996; Claramunt et al. 2020; Cline et al. 2011; Granatstein et al. 2003; Liburd et al. 1998; Puka-Beals and Gramig 2021; Warnick et al. 2006a, 2006b). Early evaluations of vegetable production systems in Florida showed soil under hydromulch made with cotton (*Gossypium hirsutum*) waste, newsprint, gypsum, and a proprietary adhesive was 1 to 4 °C cooler than soil covered by PE mulch (Warnick et al. 2006a). Soil temperature fluctuations and overall evaporative water loss following rainfall were also minimized compared with those of bare soil using a hydromulch made with 100% virgin wood chips in North Dakota (O'Brien et al. 2018). Yet, soil moisture under hydromulch can be lower compared with that under PE mulch in the absence of rainfall based on the work performed in Florida by Warnick et al. (2006a); furthermore, soil moisture may also be influenced by hydromulch material properties and application rates. Because seed germination and seedling growth can be inhibited by extreme temperature fluctuations (Kader et al. 2017), the temperature buffering capacity of hydromulch may improve conditions for

Fig. 2. Hydromulch application in field conditions. Hydromulch may be made with polysaccharides such as cellulose or hydrolyzed proteins, and a tackifier may be added. They are sprayed on the soil surface. When they dry, they create a mulch barrier. They can be made with fully biobased ingredients and are a possible alternative to plastic mulches. Photo credit: Lisa Wasko DeVetter.

vegetative establishment in certain production regions. Increased moisture conservation and soil temperature modification by lowering soil temperature were found to be beneficial for orchard production in the semi-arid region of the southern interior of British Columbia, Canada, when using a hydromulch made of recycled waste newsprint fiber mixed with longer reinforcing fibers derived from cereal or flax (*Linum usitatissimum*) straw (Cline et al. 2011). Taken together, these findings suggest that hot and semi-arid crop production regions might particularly benefit from the use of hydromulch because of its ability to moderate soil temperature (especially decreasing soil temperature in arid regions) and decrease soil evaporation rates; however, irrigation will likely remain necessary (O'Brien et al. 2018).

Cellulose-based hydromulches can contribute to the management of certain weed species, whereas other weed species may require additional management approaches, stronger hydromulch formulations, or higher rates. Recent work by Ahmad et al. (2024) showed hydromulches applied to day-neutral strawberry (*Fragaria* ×*ananassa*) systems in North Dakota and Washington suppressed weeds, but formulations containing 2% and 6% guar gum tackifier provided superior weed suppression at peak weed emergence compared with that of other formulations with no tackifier or psyllium husk as the tackifier. Broadleaf weed species appear to be more easily managed by hydromulch, whereas nutsedge (*Cyperus* spp.) has been documented to penetrate and grow through hydromulch formulations evaluated in Florida (Warnick et al. 2006a, 2006b). More recent work with hydromulches made from wheat (*Triticum* spp.) straw, rice (*Oryza sativa*) hulls, mushroom substrate, recycled paper, pulp blends, and gypsum showed reduced large crabgrass (*Digitaria sanguinalis*), redwoot pigweed (*Amaranthus retroflexus*), prickly lettuce (*Lactuca serriola*), and sowthistle (*Sonchus oleraceus*) weed seedling emergence (reduced by 65% to 95%) when compared with the untreated control under climate-controlled greenhouse conditions (Claramunt et al. 2020). Although nutsedge was not considered, this study highlights the potential of using paper-based fibers as a reinforcement for weed-suppressive hydromulch and the opportunity for additional research to determine the best components (e.g., fibers, tackifiers) to formulate hydromulches that can suppress a broader range of weed species. Hydromulch thickness (i.e., application rate) is another important consideration that governs weed-suppressive ability. Weed suppression was achieved with 1- and 2-cm-thick application depths of hydromulch made with 75% newsprint, 25% corrugated cardboard, and water using laboratory-grown and field-grown corn (*Zea mays*), but the thicker mulch was more effective at smothering weeds that had already emerged (Granatstein et al. 2003). Study results with field-grown kale (*Brassica oleracea* var. *sabellica*) in Nebraska indicated that using hydromulch [formulated with corn starch, glycerol, keratin hydrolysate, corn gluten meal, corn zein, eggshells, and isolated soy (*Glycine max*) protein] after weed emergence could offer growers greater flexibility in application timing (Gloeb et al. 2023). Additional horticultural benefits were observed with the growth of both corn and onion *(Allium cepa*) enhanced in greenhouse trials when grown with hydromulch applied after the emergence of seedlings. Granatstein et al. (2003) observed similar results in greenhouse-house grown corn using a hydromulch made with 75% newsprint paper and 25% corrugated cardboard (both recycled). Hydromulch made with recycled newsprint paper also demonstrated efficacy in facilitating the growth and establishment of young, field-grown apple (*Malus* ×*domestica*) trees in the Pacific Northwest, and weed suppression was also superior when hydromulch was compared with glyphosate checks (Cline at al. 2011).

Hydromulches with unique material characteristics can be derived from other naturally occurring polysaccharides beyond cellulose and prepared in accordance with organic production guidelines. Most polysaccharides are water-soluble and interact with water molecules, producing swelling, gelling, emulsifying, and film-forming properties (Malinconico et al. 2008). Once sprayed onto the soil surface, these mulches create a thin, protective "geomembrane" mulch layer, which hardens as water evaporates to form a protective polymeric network (Immirzi et al. 2009). Examples of natural polysaccharide ingredients beyond cellulose that could be organically sourced for mulch application include sodium alginate, galactomannan, glucomannan, agarose, and chitosan. The use of these polysaccharides offers biodegradability, biocompatibility with crops, and nontoxicity to crops and the environment while forming a mulch layer with a water-resistant coating (Avella et al. 2007; Biocore Agri 2005; Immirzi et al. 2009; Schettini et al. 2007; Vox et al. 2013). Additionally, typical spray equipment used for the application of pesticides, fertilizers, plant growth regulators, or other products could potentially be used for the application of this mulch technology, which would provide a tremendous advantage to farmers who already have and are familiar with operating this type of equipment. In contrast, cellulose-based hydromulches typically require specialized application equipment, potentially because of the size of cellulose fibers that might not dissolve in solution and clog traditional spray equipment and nozzle.

Seaweed is a promising source of polysaccharides with the potential for hydromulch formulations. Seaweeds have long been used in agriculture as fertilizers, biostimulants, and soil conditioners, with their first documented use in ancient Rome (Battacharyya et al. 2015; Merino et al. 2021; Pereira and Cotas 2019). Brown seaweeds, like wakame (*Undaria pinnatifida*), contain phytohormones or similar compounds such as indoleacetic acid, gibberellic acid, abscisic acid, and other various oligosaccharides and polysaccharides that contain biostimulant properties (Merino et al. 2021). Some seaweed species, unfortunately, represent an environmental concern in several countries because of their abundance and uncontrollable proliferation as invasive species. Thus, careful use of invasive seaweed species as a mulch biofeedstock may provide a solution to the issue of seaweed overpopulation while offering added value to crop production through biostimulant effects and serving as a carbon sequestration resource (Battacharyya et al. 2015; Kaladharan et al. 2009; Merino et al. 2021).

Polymers of sodium alginate (NaAlg) have been specifically investigated for their potential as an ingredient in hydromulch (Avella et al. 2007; Immirzi et al. 2009; Liu et al. 2013; Merino et al. 2021; Santagata et al. 2014; Vox et al. 2013; Wade et al. 2021). Studies reported that NaAlg is a component of seaweed cell walls that can enhance plant and root growth as well as tolerance to salt stress (Battacharyya et al. 2015; Liu et al. 2013; Merino et al. 2021; Salcedo et al. 2020; Zhang et al. 2014). In a water solution, especially when there are divalent cations like calcium, the unique structure of NaAlg G-blocks causes them to form insoluble gels. This happens because the divalent cations interact strongly with the ionized carboxyl ($COO-$) groups of the guluronic acid–base residue, creating a stable, insoluble three-dimensional structure known as an "egg box" (Grant et al. 1973). Furthermore, a strong interaction between NaAlg and soil calcium provides water resistance, ultimately contributing to increased mulch durability during irrigation events (Immirzi et al. 2009). The first documented use of NaAlg extracted from seaweed and formulated into a sprayable mulch was performed in tunnel-grown strawberry in Italy (Immirzi et al. 2009). The tested material provided an adequate mulch layer that lasted 6 months. However, a few cracks appeared during the first month of the experiment, allowing for weed germination and growth. This challenge should be considered when using NaAlg-based mulch, and increased application rates might be necessary.

More recent work has focused on using the invasive seaweed, wakame (*Undaria pinnatifida*), as a source of NaAlg within sprayable mulch formulations. Merino et al. (2021) developed and examined three novel formulations of sprayable mulch that included NaAlg and glycerol supplemented with different rates of wakame in a greenhouse trial using tomato (*Lycopersicon esculentum*). Soil temperatures under the evaluated formulations were 1.5 to 3 °C lower than those with PE mulch; these results highlight the potential for sprayable mulches containing NaAlg to be useful for summer crops or in climates where additional soil warming effects are not required to optimize crop growth. Although tomato plants mulched with PE had greater growth and yield than those with all sprayable mulch formulations containing wakame, formulations containing 1% wakame outperformed those with 0.5% and 2%, indicating there is an optimal wakame concentration for the highest crop growth. Soil biological properties can also be influenced by NaAlg incorporation and may be beneficial to fungal symbionts, such as mycorrhizae (Ishii et al. 2003; Khan et al. 2009; Kuwada et al. 2006; Merino et al. 2021). The addition of plasticizing polymers such as hydroxyethylcellulose and natural plasticizers such as glycerol and polyglycerol may be used to improve the mechanical properties of sprayable mulch made with NaAlg (Malinconico et al. 2008).

Mulches are frequently associated with benefits in open-field horticultural crop production; however, initial experiments with polysaccharide-based hydromulch indicate these materials could benefit potted plants or plants grown in trays in greenhouse or nursery production systems (Immirzi et al. 2009; Schettini et al. 2007; Vox et al. 2013). Chitosan-based mulch sprays have provided better weed suppression than oxadiazon herbicide sprays in container plant production, with the sprayable mulch layer lasting more than 2 months before weed seedling emergence occurred (Giaccone et al. 2018). Glucomannans (derived from roots of *Amorphophallus konjac*) combined with polyamide primers (PSS20) have also shown potential as a sprayable mulch when suspended in water and applied in greenhouse snapdragon (*Antirrhinum majus*) cultivation (Schettini et al. 2007). The glucomannan-containing sprayable mulch degraded completely within 1 to 5 months after application and provided sufficient weed suppression and tensile strength (Schettini et al. 2007; Vox et al. 2013). Such rapid degradation rates would be ideal for crops that establish quickly, such as broccoli (*Brassica oleracea*), and benefit from mulch for a short window of time. Overall, hydromulches offer a unique opportunity for greenhouse and nursery production in addition to open-field production. As a sprayable mulch, hydromulches could be reapplied if necessary to manage weeds that emerge over time and eliminate or reduce the need for herbicide applications (Giaccone et al. 2018; Schettini et al. 2007). The rapid mulch degradation rate could also be advantageous because mulch removal would not be required, thereby eliminating added labor; therefore, it is ideal for retailers who do not want to sell plants with deteriorated mulch.

Hydromulches made from cellulose and other polysaccharides show promise in organic and sustainable agriculture, but they require further investigation before commercialization. Future areas of research to consider include the development of formulations that increase soil temperature for crops and regions that benefit from soil warming so they perform similarly to traditional mulch films such as PE mulch (Merino et al. 2021). Some research has already focused on optimizing the formulation of hydromulches. Research formulations have included additional ingredients, such as locust bean gum, guar gum, agarose, glycerol, vegetable polysaccharides with cellulose-reinforcing fibers, NaAlg in combination with hydroxyethylcellulose, and polyglycerol. These ingredients alter properties such as elasticity, hydrophobicity (waterproofing), and opaqueness (Malinconico et al. 2008). Hydrolyzed proteins are another potential feedstock source that can be derived from waste products generated in the leather industry, with functional polyethylene glycol used as a crosslinking agent (Sartore et al. 2013, 2018). Additional research of application technologies, rates, and cost-benefits is also needed and justified based on promising initial work. Hydromulch has the alluring potential to use waste as its feedstock source, creating a more closed-loop system. Nevertheless, the water requirements needed to make and apply hydromulch should be considered in future life cycle assessments of the technology. Hydromulch feedstock materials could contribute to soil health if they function as beneficial amendments when incorporated into soil; however, research is required because the high carbon content of hydromulch could immobilize nitrogen and possibly impact the availability of other nutrients. Contamination of hydromulch and other paper-based mulches with perfluoroalkoxy and polyfluoroalkyl substances ("forever chemicals") has also emerged as a concern (Weiss et al. 2024).

Foam Mulches

Foam mulches are an emerging concept because they have dual purposes as mulch when applied directly to the ground and as a protectant when applied to plant surfaces (Choi and Giacomelli 1999). Foam mulches can be applied as aqueous foam, maintaining their structural integrity throughout a growing season and potentially providing weed suppression similar to PE mulch (Masiunas et al. 2003). One of the first documented foam mulch formulations was developed by Choi and Giacomelli (1999) using sucrose as a bulking agent and gelatin as a polymeric material. The foam mulch was tested using lettuce (*Lactuca sativa*). Interestingly, daytime soil temperatures under the thinner foam mulch were consistently warmer than those under the thicker foam mulch. This difference was attributed to shortwave solar radiation penetrating the thin foam layer and being absorbed by the soil surface. Blue foam mulch made with a mixture of cotton and cellulose fibers, gums, starches, surfactants, and saponins increased the yield of basil (*Ocimum basilicum*) and tomato compared with those under red and black foam mulch and an unmulched control. Similarly, all colors of foam mulch provided weed suppression comparable to that of PE mulch (Masiunas et al. 2003). These findings demonstrate the importance of mulch color on crop productivity. Overall, foam mulch holds promise as an organic alternative mulching material as long as all constituents are organic-approved. Foam mulch could be enhanced by incorporating biological control agents, pesticides, and/or foliar fertilizer, thus providing other plant growth benefits (Choi and Giacomelli 1999); however, more testing is required. Concerns associated with foam mulch include cost, development, application equipment needs, potential negative impacts on crops, availability, and durability under diverse field growing conditions.

Biobased Agrotextiles

Agrotextiles are classified as geotextiles that have been manufactured for specific use in agriculture, horticulture, fishing, forestry, animal husbandry, landscaping, gardening, aquaculture, or agro-engineering purposes (Chowdhury et al. 2017). Some of the agricultural and horticultural applications of agrotextiles include shade cloths, greenhouse covers, and mulch mats (e.g., "weed mat"). Agrotextiles used for mulching are typically made from synthetic polymers, including polypropylene and polyethylene, and are either woven or nonwoven. Natural fibers such as jute (*Corchorus olitorius* or *C. olitorius*) and coco coir (derived from *Cocos nucifera*) may also be used (Adhikary and Pal 2019; Prambauer et al. 2019; Reddy and Pal 2021) as shade cloth, but they are usually not suitable for weed control because of their loose mesh and light porosity. Agrotextiles made with biobased ingredients are often referred to as "biofabrics" and include spunbond, nonwoven fabrics composed of polylactic acid (PLA) or PLA in combination with polyhydroxyalkanoate or aliphatic-aromatic copolymers (Cowan et al. 2013; Thompson et al. 2019) (Fig. 3).

Biofabrics must meet the biodegradation standards of ASTM D5988/ISO 17556 required for organic production in the US, particularly if the biofabric will not be removed from the field after use (Thompson et al. 2019). Biofabrics made with PLA are expected to biodegrade more slowly in ambient soil conditions because of the high glass transition temperature of PLA (63 °C), which could be a barrier to adoption and use as a soil-biodegradable alternative to conventional plastics (Pietrosanto et al. 2020; Rudnik and Briassoulis 2011a, 2011b). Although PLA is unlikely to meet biodegradation standards in soil (although PLA readily degrades in industrial composting conditions), degradation in soil can be accelerated by adding cellulose, starch, and other plant-based particles to a biofabric composite. Combining PLA with starch can cause quicker degradation in soil compared with PLA alone (Lu et al. 2009; Schwach and Avérous 2004). Thompson et al. (2019) tested PLA biofabric blended with alfalfa (*Medicago sativa*) or soy particles to accelerate the degradation of PLA in soil and found that the presence of plant-based particles reduced the molecular weight of PLA during biodegradation in soil compared with PLA alone. Combining PLA with particles of soy, wheat straw, or peanut (*Arachis hypogaea*) shells in a biofabric composite can accelerate the biodegradation of PLA in compost, where temperatures exceed the PLA glass transition temperature (Pradhan et al. 2010; Yamoum and Magaraphan 2017); however, degradation is considerably slower in soil (Thompson et al. 2019).

Preliminary trials with an experimental PLA biofabric weed barrier demonstrated beneficial effects, including increased relative soil moisture throughout the growing season, season-long weed suppression, and greater durability throughout the season compared with film-based BDMs (Cowan et al. 2013; Miles et al. 2012; Wortman et al. 2015, 2016). One advantage of biofabric mulch is its ability to remain intact in the field following the growing season. This durability could allow for reuse and double cropping applications as well as removal and disposal at a commercial composting facility because most PLA biomaterials are certified compostable (Miles et al. 2012). Yet, PLA is infrequently composted at present and may be considered a polymer contaminant in composting operations (Pierre Sarazin, personal communication). The possibility of in-soil biodegradation has been studied as a possible end-of-life pathway for PLA biofabrics; however, >10% PLA residues have been found in soil for at least 2 years following incorporation (Samuelson et al. 2022; Wortman et al. 2016). Therefore, PLA may not be incorporated in soil on certified organic farms in the US (but could be completely removed and composted). Samuelson et al. (2022) explored the possibility of speeding in-soil degradation of PLA biofabrics with cover crops, compost, and compost extracts. Still, management efforts had no effects on degradation rates, which plateaued after wood particles embedded in the PLA composite had degraded. Reid et al. (2022) found evidence that PLA biofabric residue in soil can immobilize nitrate and reduce the yield of subsequent crops, particularly in soils with lower fertility, further supporting commercial composting as the most appropriate end-of-life pathway for PLA biofabrics.

Crop yields in cooler climates are often greater for bioplastic films than for biofabrics because of the greater soil warming impacts from films (Miles et al. 2012; Wortman et al. 2016). Bioplastic films typically absorb and transfer solar radiation to the soil, leading to increased temperatures, whereas biofabrics and organic mulches are generally less effective conductors of heat and can cause decreased soil temperatures (Larsson and Bath 1996; Wortman et al. 2016). Wortman et al. (2015, 2016) suggested that the use of biofabrics might be most feasible for cool-season crops, in high tunnels, or in warmer climates, where soil temperatures are usually already within acceptable ranges, and weed control as well as soil moisture conservation are still critical. The PLA biofabric is also gas and water-permeable, which can help prevent oversaturated soil conditions that sometimes lead to the incidence of *Pythium* sp. and other soilborne damping-off diseases (Wortman et al. 2015). Although PLA biofabric mulch offers unique benefits compared with PE and BDM mulch films, it is also considerably thicker and heavier (because it is spunbond, nonwoven, and not extruded like film), resulting in a higher manufacturing and retail costs to the grower. Based on a similar surface area, currently, PLA-based biofabrics are approximately two-times more expensive than BDM films and four-times more expensive than PE films but comparable to paper mulch and polypropylene agrotextiles (Sam Wortman, personal communication). Given this limitation as a replacement for PE and BDM, new research has focused on the development of PLA biofabrics for weed control in high-density, narrowly spaced, direct-seeded horticultural crops such as lettuce and carrot (*Daucus carota)*.

Mulch films and fabrics are usually not compatible for use in high-density, narrowly spaced crops because the number of holes required in the barrier to facilitate plant establishment would limit its utility as a weed barrier. Because PLA biofabrics are nonwoven and permeable to air and water, it may be possible for them to act as a selective membrane, allowing crop root growth from above while suppressing weed shoots below. Tofanelli et al. (2021) tested the concept of using PLA biofabrics as a weed barrier for densely seeded carrots and lettuce; seeds were planted directly on the biofabric, covered with soilless media, germinated, and successfully rooted through and established in the biofabric. The result was a biobased geotextile weed barrier without any holes typically needed in a weed barrier, and the biofabric membrane expanded with the developing roots (Tofanelli et al. 2021). During a pot study that compared

Fig. 3. Biobased agrotextiles made from polylactic acid (PLA) can be used as a traditional weed barrier (pumpkins, top left) or to grow direct-seeded or narrowly spaced crops such as sunflower (top right), matted-row strawberry (bottom left), and carrot (bottom right). The seedlings grow and root through the barrier from above. Photo credit: Sam Wortman.

biofabric to bare soil, there were no negative effects of the biofabric on crop establishment and growth, and lettuce growth increased by 72% when the fabric was enriched with soybean meal particles (Tofanelli et al. 2021). Wehrbein et al. (2024) tested this concept in open-field carrot production. They found that PLA biofabric reduced weed density by 90% and did not negatively affect yield (yield benefits of the biofabric compared with bare soil were not documented because weeds were removed by hand weekly). The carbon-rich content of the PLA biofabric immobilized soil nitrate and reduced plant availability by 47% (Wehrbein et al. 2024). However, enriching the biofabric with nitrogen-rich soybean meal particles may help mitigate this potentially negative effects (Tofanelli et al. 2021). Ongoing research will explore the feasibility and potential benefits of fertilizer-enriched biofabrics in carrot and lettuce production.

Challenges and Future Directions

Concerns about soil–plastic pollution caused by the heavy reliance of farming on plastic use are relatively recent but continue to grow (Boots et al. 2019; Madrid et al. 2022). Agricultural practices such as mulching with plastics are a significant route for microplastic and nanoplastic entry into livestock farming, and plants have also been documented to bioaccumulate plastic particles (Li et al. 2020a, 2020b; Ramachandraiah et al. 2022; Wang et al. 2020, 2022). Continued efforts should be focused on understanding the scope and impacts of plastic pollution in the environment and effective mitigation measures that reduce the entry of harmful plastics into agroecosystems and the surrounding environment. Such mitigation measures should be developed with an understanding of farming systems and related production constraints to ensure that producers have access to affordable and effective mulch options or other suitable alternatives. Additionally, mitigation approaches should be supported by robust research that is extended to the agricultural community and policymakers so that resultant policies and regulations are scientifically grounded. Any economic disadvantages for producers to switch to alternatives that reduce plastic waste generation and pollution should be offset by incentives or compensation to eliminate financial burdens at the farm level. Evolving extended producer responsibility laws should also consider mulch and resin manufacturers and avoid placing sole responsibility on growers.

The Food and Agriculture Organization outlined the "6R" approach to enhance sustainable outcomes of agricultural plastics; this approach includes refuse, reduce, reuse, recycle, recover, and redesign (Food and Agriculture Organization 2021). The 6Rs are based on definitions made by the European Union (European Parliament and the Council 2008; Zero Waste Europe 2019). Biodegradable mulches fall within the redesign approach but still need continued development and exploration to broaden the range of affordable mulch options available for conventional, organic, and sustainable farming operations. Cost-effectiveness is of paramount importance for on-farm adoption, and biodegradable mulches could be more economical in the long term if mulch removal and disposal costs can be eliminated (Galinato et al. 2020; Velandia et al. 2018, 2019). Therefore, biodegradable mulches can offer significant economic benefits by reducing long-term costs associated with mulch removal and disposal in addition to environmental benefits.

The potential impact that different mulching materials might have on soil health, crop productivity, and crop quality should be considered when investigating and ultimately selecting or promoting a mulch type in agricultural operations. Novel, organic-based mulches such as hydromulches derived from polysaccharides might offer some benefits through their degradation and breakdown, such as increased soil carbon and replenishment of minerals taken up by the crop. However, breakdown of organic mulches in soils can also lead to nutrient imbalances in some cases, which can be associated with yield loss. Unfortunately, the high carbon:nitrogen ratio of hydromulches can potentially limit yields (Gloeb et al. 2023; Puka-Beals and Gramig 2021) because of soil nitrogen immobilization (Booth et al. 2005; Wehrbein et al. 2024). Emerging mulch technologies should use materials with carbon:nitrogen ratios that do not lead to nitrogen immobilization. Alternatively, deployment could be aligned with farming practices that minimize the negative impact of immobilization on the crop via increased nitrogen supply. Adding nutrients, biostimulants, and pesticides may also be useful when designing multifunctional mulches with added value beyond modifying soil temperature and moisture and suppressing weeds. New soil-biodegradable and biobased mulch technologies should be explored in parallel with other technologies that improve the end-of-life outcomes of nonbiodegradable plastic mulches including improved PE mulch retrieval and recycling strategies.

References Cited

Adhikary R, Pal A. 2019. Geotextile and its importance in Agriculture: A review study. IJBS. 6(2):61–63. https://doi.org/10.30954/2347-9655.02.2019.3.

Ahmad W, DeVetter LW, McFadden D, Maupin B, Bajwa DS, Durado A, Weyers S, Galinato SP, Weiss B, Gramig G. 2024. Hydromulches suppress weeds and maintain fruit production in organically managed strawberry systems. Front Agron. 6(1375505). https://doi.org/10.3389/fagro.2024.1375505.

Anderson DF, Garisto MA, Bourrut JC, Schonbeck MW, Jaye R, Wurzberger A, DeGregorio R. 1996. Evaluation of a paper mulch made from recycled materials as an alternative to plastic film mulch for vegetables. J Sustain Agric. 7(1):39–61. https://doi.org/10.1300/J064v07n01_05.

Avella M, Pace ED, Immirzi B, Impallomeni G, Malinconico M, Santagata G. 2007. Addition of glycerol plasticizer to seaweeds derived alginates: Influence of microstructure on chemical–physical properties. Carbohydr Polym. 69(3):503–511. https://doi.org/10.1016/j.carbpol.2007.01.011.

Bandopadhyay S, Martin-Closas L, Pelacho AM, DeBruyn JM. 2018. Biodegradable plastic mulch films: Impacts on soil microbial communities and ecosystem functions. Front Microbiol. 9:819. https://doi.org/10.3389/fmicb.2018.00819.

Battacharyya D, Babgohari MZ, Rathor P, Prithiviraj B. 2015. Seaweed extracts as biostimulants in horticulture. Sci Hortic. 196:39–48. https://doi.org/10.1016/j.scienta.2015.09.012.

Bettas Ardisson G, Tosin M, Barbale M, Degli-Innocenti F. 2014. Biodegradation of plastics in soil and effects on nitrification activity. A laboratory approach. Front Microbiol. 5:710. https://doi.org/10.3389/fmicb.2014.00710.

Biocor Agri. 2005. EU Project Biodegradable coverages for sustainable agriculture. Contract no. LIFE03 ENV/IT/000377. http://www.ictp.cnr.it/life/index.htmlS.

Booth MS, Stark JM, Rastetter E. 2005. Controls on nitrogen cycling in terrestrial ecosystems: A synthetic analysis of literature data. Ecol Monogr. 75(2):139–157. https://doi.org/10.1890/04-0988.

Boots B, Russell CW, Green DS. 2019. Effects of microplastics in soil ecosystems: Above and below ground. Environ Sci Technol. 53(19):11496–11506. https://doi.org/10.1021/acs.est.9b03304.

Briassoulis D, Hiskakis M, Scarascia G, Picuno P, Delgado C, Dejean C. 2010. Labeling scheme for agricultural plastic wastes in Europe. Qual Assur Saf Crops Foods. 2(2):93–104. https://doi.org/10.1111/j.1757-837X.2010.00061.x.

Brodhagen M, Peyron M, Miles C, Inglis DA. 2015. Biodegradable plastic agricultural mulches and key features of microbial degradation. Appl Microbiol Biotechnol. 99(3):1039–1056. https://doi.org/10.1007/s00253-014-6267-5.

Brodhagen M, Goldberger JR, Hayes DG, Inglis DA, Marsh TL, Miles C. 2017. Policy considerations for limiting unintended residual plastic in agricultural soils. Environ Sci Policy. 69:81–84. https://doi.org/10.1016/j.envsci.2016.12.014.

Choi CY, Giacomelli G. 1999. Freeze and frost protection with aqueous foam-field experiments. HortTechnology. 9(4):670–676. https://doi.org/10.21273/HORTTECH.9.4.670.

Chowdhury MJ, Nasrin S, Al Faruque MA. 2017. Significance of agro-textiles and future prospects in Bangladesh. ESJ. 13(21):139–7881. https://doi.org/10.19044/esj.2017.v13n21p139.

Claramunt J, Mas MT, Pardo G, Cirujeda A, Verdú AMC. 2020. Mechanical characterization of blends containing recycled paper pulp and other lignocellulosic materials to develop hydromulches for weed control. Biosyst Eng. 191:35–47. https://doi.org/10.1016/j.biosystemseng.2019.12.012.

Cline J, Neilsen G, Hogue E, Kuchta S, Neilsen D. 2011. Spray-on-mulch technology for intensively grown irrigated apple orchards: Influence on tree establishment, early yields, and soil physical properties. HortTechnology. 21(4):398–411. https://doi.org/10.21273/HORTTECH.21.4.398.

Cole M, Lindeque P, Halsband C, Galloway TS. 2011. Microplastics as contaminants in the marine environment: A review. Mar Pollut Bull. 62(12):2588–2597. https://doi.org/10.1016/j.marpolbul.2011.09.025.

Cowan JS, Miles CA, Andrews PK, Inglis DA. 2013. Biodegradable mulch performed comparably to polyethylene in high tunnel tomato (*Solanum lycopersicum* L.) production. J Sci Food Agric. 94(9):1854–1864. https://doi.org/10.1002/jsfa.6504.

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

DeVetter LW, Shrestha S, Hayes D. 2021. What is a soil-biodegradable plastic mulch composed of? Plastic mulch use and management. https://s3.wp.wsu.edu/uploads/sites/2181/2021/07/What-is-in-a-BDM.pdf.

Faucette LB, Risse LM, Jordan CF, Cabrera ML, Coleman DC, West LT. 2006. Vegetation and soil quality effects from hydroseed and compost blankets used for erosion control in construction activities. J Soil Water Conservation. 61(6):355–362.

Food and Agriculture Organization. 2021. Assessment of agricultural plastics and their sustainability—A call for action. Food and Agriculture Organization. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1460015/.

Galinato SP, Velandia M, Ghimire S. 2020. Economic feasibility of using alternative plastic mulches: Case study for pumpkin in western Washington. Washington State University Extension Publication TB68E. https://hdl.handle.net/2376/17726.

Gheshm R, Brown RN. 2020. Compost and black polyethylene mulches improve spring production of romaine lettuce in southern New England. HortTechnology. 30(4):510–518. https://doi.org/10.21273/HORTTECH04594-20.

Giaccone M, Cirillo C, Scognamiglio P, Teobaldelli M, Mataffo A, Stinca A, Pannico A, Immirzi B, Santagata G, Malinconico M, Basile B. 2018. Biodegradable mulching spray for weed control in the cultivation of containerized ornamental shrubs. Chem Biol Technol Agric. 5(1):21. https://doi.org/10.1186/s40538-018-0134-z.

Gloeb E, Irmak S, Isom L, Lindquist JL, Wortman SE. 2023. Biobased sprayable mulch films suppressed annual weeds in vegetable crops. HortTechnology. 33(1):27–35. https://doi.org/10.21273/HORTTECH05112-22.

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

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

Granatstein D, McErlich Hogue E. 2003. Sprayable paper mulch for organic row crop production. Washington State University, Pullman, WA, USA. https://doi.org/10.7273/000002565.

Grant GT, Morris ER, Rees DA, Smith PJ, Thom D. 1973. Biological interactions between polysaccharides and divalent cations: The egg-box model. FEBS Letters. 32(1):195–198. https://doi.org/10.1016/0014-5793(73)80770-7.

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

Haapala T, Palonen P, Korpela A, Ahokas J. 2014. Feasibility of paper mulches in crop production: A review. AFSci. 23(1):60–79. http://hdl.handle.net/10138/165408. https://doi.org/10.23986/afsci.8542.

Hansford WB. 1981. Sprayable hydromulch. US Patent US4297810A. https://patents.google.com/patent/US4297810A/en.

Hayes DG, Flury M. 2018. Summary and assessment of EN 17033: 2018, a new standard for biodegradable plastic mulch films. Rpt. No. EXT-2018-01. http://www.biodegradablemulch.org/.

Immirzi B, Santagata G, Vox G, Schettini E. 2009. Preparation, characterisation and field-testing of a biodegradable sodium alginate-based spray mulch. Biosyst Eng. 102(4):461–472. https://doi.org/10.1016/j.biosystemseng.2008.12.008.

Iriany A, Chanan M, Djoyowasito G. 2018. Organic mulch sheet formulation as an effort to help plants adapt to climate change. Int J Recycl Org Waste Agricult. 7(1):41–47. https://doi.org/10.1007/s40093-017-0189-z.

Ishii T, Kitabayashi H, Aikawa J, Matsumoto I, Kadoya K, Kirino S. 2003. Effects of alginate oligosaccharide and polyamines on hyphal growth of vesicular-arbuscular mycorrhizal fungi and their infectivity of citrus roots. In: Proceedings International Society of Citriculture 1030–1032. https://doi.org/10.2503/jjshs.73.529.

Kader MA, Senge M, Mojid MA, Nakamura K. 2017. Mulching type-induced soil moisture and temperature regimes and water use efficiency of soybean under rain-fed condition in central Japan. Int Soil Water Conservation Res. 5(4):302–308. https://doi.org/10.1016/j.iswcr.2017.08.001.

Kaladharan P, Veena S, Vivekanandan E. 2009. Carbon sequestration by a few marine algae: Observation and projection. J Mar Biol Assoc India. 51(1):107–110. http://eprints.cmfri.org.in/id/eprint/2212.

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

Khan W, Rayirath UP, Subramanian S, Jithesh MN, Rayorath P, Hodges DM, Critchley AT, Craigie JS, Norrie J, Prithiviraj B. 2009. Seaweed extracts as biostimulants of plant growth and development. J Plant Growth Regul. 28(4):386–399. https://doi.org/10.1007/s00344-009-9103-x.

Kuwada K, Wamocho LS, Utamura M, Matsushita I, Ishii T. 2006. Effect of red and green algal extracts on hyphal growth of arbuscular mycorrhizal fungi, and on mycorrhizal development and growth of papaya and passionfruit. Agron J. 98(5):1340–1344. https://doi.org/10.2134/agronj2005.0354.

Kyrikou I, Briassoulis D. 2007. Biodegradation of agricultural plastic films: A critical review. J Polym Environ. 15(2):125–150. http://dx.doi.org/10.1007/s10924-007-0063-6.

Larsson L, Bath A. 1996. Evaluation of soil temperature moderating and moisture conserving effects of various mulches during a growing season. J Agric Scand Sect B Soil Plant Sci. 46(3):153–160. https://doi.org/10.1080/09064719609413128.

Leary J, DeFrank J. 2000. Living mulches for organic farming systems. HortTechnology. 10(4): 692–698. https://doi.org/10.21273/HORTTECH.10.4.692.

Li C, Moore-Kucera J, Miles C, Leonas K, Lee J, Corbin A, Inglis D. 2014. Degradation of potentially biodegradable plastic mulch films at three diverse U.S. locations. Agroecol Sustain Food Syst. 38(8):861–889. https://doi.org/10.1080/21683565.2014.884515.

Li L, Luo Y, Li R, Zhou Q, Peijnenburg WJ, Yin N, Yang J, Tu C, Zhang Y. 2020a. Effective uptake of submicrometre plastics by crop plants via a crack-entry mode. Nat Sustain. 3(11): 929–937. https://doi.org/10.1038/s41893-020-0567-9.

Liu H, Zhang YH, Yin H, Wang WX, Zhao XM, Du YG. 2013. Alginate oligosaccharides enhanced *Triticum aestivum* L. tolerance to drought stress. Plant Physiol Biochem. 62:33–40. http://dx.doi.org/10.1016/j.plaphy.2012.10.012.

Liburd OE, Casagrande RA, Alm SR. 1998. Evaluation of various color hydromulches and weed fabric on broccoli insect populations. J Econ Entomol. 91(1):256–262. https://doi.org/10.1093/jee/91.1.256.

López-Marín J, Romero M, Gálvez A, del Amor FM, Piñero MC, Brotons-Martínez JM. 2021. The use of hydromulching as an alternative to plastic films in an artichoke (*Cynara cardunculus* cv. Symphony) crop: A study of economic viability. Sustainability. 13(9):5313. https://doi.org/10.3390/su13095313.

Lu DR, Xiao CM, Xu SJ. 2009. Starch-based completely biodegradable polymer materials. Express Polym Lett. 3(6):366–375. https://doi.org/10.3144/expresspolymlett.2009.46.

Madrid B, Wortman S, Hayes DG, DeBruyn JM, Miles C, Flury M, Marsh TL, Galinato SP, Englund K, Agehara S, DeVetter LW. 2022. End-of-life management options for agricultural mulch films in the United States. A review. Front Sustain Food Syst. 6:921496. https://doi.org/10.3389/fsufs.2022.921496.

Malinconico M, Immirzi B, Santagata G, Schettini E, Vox G, Mugnozza GS. 2008. An overview on innovative biodegradable materials for agricultural applications, p 69–114. In: Moeller HW (ed). Progress in Polymer Degradation and Stability Research. Nova Science Publishers, Inc., New York, NY, USA.

Mas MT, Pardo G, Pueyo J, Verdu AMC, Cirujeda A. 2021. Can hydromulch reduce the emergence of perennial weeds? Agronomy. 11(2):393. https://doi.org/10.3390/agronomy11020393.

Masiunas J, Wahle E, Barmore L, Morgan A. 2003. A foam mulching system to control weeds in tomatoes and sweet basil. HortTechnology. 13(2):324–328. https://doi.org/10.21273/HORTTECH.13.2.0324.

Merino D, Salcedo MF, Mansilla AY, Casalongue CA, Alvarez VA. 2021. Development of sprayable sodium alginate-seaweed agricultural mulches with nutritional benefits for substrates and plants. Waste Biomass Valor. 12(11):6035–6043. https://doi.org/10.1007/s12649-021-01441-x.

Miles C, DeVetter L, Ghimire S, Hayes DG. 2017. Suitability of biodegradable plastic mulches for organic and sustainable agricultural production systems. HortScience. 52(1):10–15. https://doi.org/10.21273/HORTSCI11249-16.

Miles C, Madrid B, DeVetter L. 2023. Soil-biodegradable plastic mulch in organic agriculture. https://s3.wp.wsu.edu/uploads/sites/2181/2021/12/BDM-Organic-Dec-2021.pdf.

Miles C, Wallace R, Wszelaki A, Martin J, Cowan J, Walters T, Inglis D. 2012. Deterioration of potentially biodegradable alternatives to black plastic mulch in three tomato production regions. HortScience. 47(9):1270–1277. https://doi.org/10.21273/HORTSCI.47.9.1270.

Moore J, Wszelaki A. 2016. Plastic mulch in fruit and vegetable production: Challenges for disposal. University of Tennessee. https://ag.tennessee.edu/biodegradablemulch/Documents/Plastic%20Mulch%20in%20Fruit%20and%20Vegetable%20Production_12_20factsheet.pdf/. accessed 22 Jan. 2021.

Moore JC, Wszelaki AL. 2019. The use of biodegradable mulches in pepper production in the southeastern United States. HortScience. 54(6):1031–1038. https://doi.org/10.21273/HORTSCI13942-19.

National Organic Program. 2022. National Organic Program; proposed amendments to the National List of Allowed and Prohibited Substances per April 2019 NOSB recommendations (livestock and handling). Federal Information and News Dispatch, LLC. https://www.federalregister.gov/documents/2022/11/14/2022-24111/amendments-to-the-national-list-of-allowed-and-prohibited-substances-per-october-2020-and-april-2021.

Nwosisi S, Nandwani D, Hui D. 2019. Mulch treatment effect on weed biomass and yields of organic sweetpotato cultivars. Agronomy. 9(4): 190. https://doi.org/10.3390/agronomy9040190.

O'Brien PL, Acharya U, Alghamdi R, Niaghi AR, Sanyal D, Wirtz J, Daigh ALM, DeSutter TM. 2018. Hydromulch application to bare soil: soil temperature dynamics and evaporative fluxes. Agric Environ Lett. 3(1):180014. https://doi.org/10.2134/ael2018.03.0014.

Organic Federation of Canada Questions and answers: Canadian organic standards Organic Federation of Canada: Canadian Organic Standards. 2018. https://www.organicfederation.ca/canadian-organic-standards. [accessed Mar 2024].

Pereira L, Cotas J. 2019. Historical use of seaweed as an agricultural fertilizer in the European Atlantic area. seaweed as plant fertilizer. Agric Biostimulants and Animal Fodder. 1:1–22. https://www.researchgate.net/publication/337223727_Seaweeds_as_Plant_Fertilizer_Agricultural_Biostimulants_and_Animal_Fodder.

Pietrosanto A, Scarfato P, Di Maio L, Rossella Nobile M, Incarnato L. 2020. Evaluation of the suitability of poly(lactide)/poly(butylene-adipate-co-aerephthalate) blown films for chilled and frozen food packaging applications. Polymers. 12(4):804. https://doi.org/10.3390/polym12040804.

Pradhan R, Misra M, Erickson L, Mohanty A. 2010. Compostability and biodegradation study of PLA-wheat straw and PLA-soy based green composites in a simulated composting bioreactor. Bioresour Technol. 101(21):8489–8491. https://doi.org/10.1016/j.biortech.2010.06.053.

Prambauer M, Wendeler C, Weitzenböck J, Burgstaller C. 2019. Biodegradable geotextiles – An overview of existing and potential materials. Geotextiles and Geomembranes. 47(1):48–59. https://doi.org/10.1016/j.geotexmem.2018.09.006.

Puka-Beals JJ, Gramig GG. 2021. Weed suppression potential of living mulches, newspaper hydromulches, and compost blankets in organically managed carrot. HortTechnology. 31(1):89–96. https://doi.org/10.21273/HORTTECH04745-20.

Ramachandraiah K, Ameer K, Jiang G, Hong GP. 2022. Micro- and nanoplastic contamination in livestock production: Entry pathways, potential effects and analytical challenges. Sci Total Environ. 844:157234. https://doi.org/10.1016/j.scitotenv.2022.157234.

Reddy DP, Pal A. 2021. Use of geotextiles in agriculture: A review study. Int J Bot Stud. 6(4): 81–83.

Reid EV, Samuelson MB, Blanco-Canqui H, Drijber R, Kadoma I, Wortman SE. 2022. Biodegradable and biobased mulch residues had limited impacts on soil properties but reduced yield of the following crop in a low fertility soil. Renew Agric Food Syst. 37(5):490–503. https://10.1017/S1742170522000217.

Romero-Muñoz M, Gálvez A, Martínez-Melgarejo PA, del Amor FM, Albacete A, López-Marín J. 2024. The use of hydromulching increases yield and quality of drought-stressed artichokes (*Cynara cardunculus* subsp. *scolymus* L. (Heidi)) by improving soil properties and plant hormone homeostasis. Plant Stress. 11:100308. https://doi.org/10.1016/j.stress.2023.100308.

Rudnik E, Briassoulis D. 2011a. Comparative biodegradation in soil behavior of two biodegradable polymers based on renewable resources. J Polym Environ. 19(1):18–39. https://doi.org/10.1007/s10924-010-0243-7.

Rudnik E, Briassoulis D. 2011b. Degradation behavior of poly (lactic acid) films and fibers in soil under Mediterranean field conditions and laboratory simulations testing. Ind Crops Products. 33(3):648–658. https://doi.org/10.1016/j.indcrop.2010.12.031.

Salcedo MF, Colman SL, Mansilla AY, Martinez MA, Fiol DF, Alvarez VA, Casalongue CA. 2020. Amelioration of tomato plants cultivated in organic-matter impoverished soil by supplementation with *Undaria pinnatifida*. Algal Res. 46:101785. https://doi.org/10.1016/j.algal.2019.101785.

Samuelson MB, Reid EV, Drijber R, Jeske E, Blanco-Canqui H, Mamo M, Kadoma I, Wortman SE. 2022. Effects of compost, cover crops, and local conditions on degradation of two agricultural mulches in soil. Renew Agric Food Syst. 37(2): 128–141. https://10.1017/S1742170511000405.

Santagata G, Malinconico M, Immirzi B, Schettini E, Mugnozza GS, Vox G. 2014. An overview of biodegradable films and spray coatings as sustainable alternative to oil-based mulching films. Acta Hortic. 1037:921–928. https://doi.org/10.17660/ActaHortic.2014.1037.122.

Sartore L, Schettini E, Palma LD, Brunetti G, Cocozza C, Vox G. 2018. Effect of hydrolyzed protein-based mulching coatings on the soil properties and productivity in a tunnel greenhouse crop system. Sci Total Environ. 645:1221–1229. https://doi.org/10.1016/j.scitotenv.2018.07.259.

Sartore L, Vox G, Schettini E. 2013. Preparation and performance of novel biodegradable polymeric materials based on hydrolyzed proteins for agricultural application. J Polym Environ. 21(3):718–725. https://doi.org/10.1007/s10924-013-0574-2.

Schettini E, Vox G, De Lucia B. 2007. Effects of the radiometric properties of innovative biodegradable mulching materials on snapdragon cultivation. Sci Hortic. 112(4):456–461. https://doi.org/10.1016/j.scienta.2007.01.013.

Schwach E, Avérous L. 2004. Starch-based biodegradable blends: Morphology and interface properties. Polymer Int. 53(12):2115–2124. https://doi.org/10.1002/pi.1636.

Shitong L, Fan D, Flury M, Zhan W, Li X, Shuangyi L, Davey J, Jingkuan W. 2022. Macro- and microplastic accumulation in soil after 32 years of plastic film mulching. Environ Pollut. 300: 118945. https://doi.org/10.1016/j.envpol.2022.118945.

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

Sintim HY, Bandopadhyay S, English ME, Bary AI, Liquet y González JE, DeBruyn JM, Schaeffer SM, Miles CA, Flury M. 2020. Four Years of continuous use of soil-biodegradable plastic mulch: Impact on soil and groundwater quality. Geoderma. 381:114665. https://doi.org/10.1016/j.geoderma.2020.114665.

Testani E, Ciaccia C, Campanelli G, Leteo F, Salvati L, Canali S. 2019. Mulch-based no-tillage effects on weed community and management in an organic vegetable system. Agronomy. 9(10):594. https://doi.org/10.3390/agronomy9100594.

Thompson AA, Samuelson MB, Kadoma I, Soto-Cantu E, Drijber R, Wortman SE. 2019. Degradation rate of bio-based agricultural mulch is influenced by mulch composition and biostimulant application. J Polym Environ. 27(3):498–509. https://doi.org/10.1007/s10924-019-01371-9.

Tofanelli MB, Kadoma I, Wortman SE. 2021. Proof of concept for growing lettuce and carrot in a biobased mulch membrane. Renew Agric Food Syst. 36(2):121–125. https://doi.org/10.1017/S1742170520000162.

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

US Department of Agriculture. 2014a. The national list of allowed and prohibited substances. US Department of Agriculture, Washington, DC. https://www.ecfr.gov/current/title-7/section-205.2.

US Department of Agriculture. 2014b. The national list of allowed and prohibited substances. US Department of Agriculture, Washington, DC. https://www.ecfr.gov/current/title-7/section-205.601.

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

Velandia M, Smith A, Wszelaki A, Galinato S, Marsh T. 2018. The economics of adopting biodegradable plastic mulch films. https://doi.org/10.22004/ag.econ.302940.

Vox G, Santagata G, Malinconico M, Immirzi B, Mugnozza GS, Schettini E. 2013. Biodegradable films and spray coatings as eco-friendly alternative to petro-chemical derived mulching films. J Agric Eng. 44(2s). http://dx.doi.org/10.4081/jae.2013.s2.e44.

Wade E, Zowada R, Foudazi R. 2021. Alginate and guar gum spray application for improving soil aggregation and soil crust integrity. Carbohydrate Polymer Technol Appl. 2:100114. https://doi.org/10.1016/j.carpta.2021.100114.

Wang W, Ge J, Yu X, Li H. 2020. Environmental fate and impacts of microplastics in soil ecosystems: Progress and perspective. Sci Total Environ. 708:134841. https://doi.org/10.1016/j.scitotenv.2019.134841.

Wang W, Yuan W, Xu EG, Li L, Zhang H, Yang Y. 2022. Uptake, translocation, and biological impacts of micro (nano) plastics in terrestrial plants: Progress and prospects. Environ Res. 203:111867. https://doi.org/10.1016/j.envres.2021.111867.

Warnick JP, Chase CA, Rosskopf EN, Simonne EH, Scholberg JM, Koenig RL, Roe NE. 2006a. Weed suppression with hydramulch, a biodegradable liquid paper mulch in development. Renew Agric Food Syst. 21(4):216–223. https://doi.org/10.1079/RAF2006154.

Warnick JP, Chase CA, Rosskopf EN, Scholberg JM, Simonne EH, Koenig RL, Roe NE. 2006b. Hydramulch for muskmelon and bell pepper crop production systems. J Veg Sci. 12(2):39–55. https://doi.org/10.1300/J484v12n02_05.

Wehrbein CD, Kadoma I, Wortman SE. 2024. First field evaluation of a polylactic acid-based weed barrier with compost for carrot production. HortTechnology. 34(2):204–210. https://doi.org/10.21273/HORTTECH05370-23.

Weiss B, Sarpong K, Miles C. 2024. PFAS are Not Present in Soil-Biodegradable Plastic Mulch. Washinton State University, Pullman, WA, USA. https://smallfruits.wsu.edu/documents/2024/03/pfas-in-bdm-factsheet.pdf/.

Wortman SE, Jeske E, Samuelson MB, Drijber R. 2022. A new method for detecting micro-fragments of biodegradable mulch films containing poly (butylene adipate-co-terephthalate) (PBAT) in soil. J Environ Qual. 51(1):123–128. https://doi.org/10.1002/jeq2.20311.

Wortman SE, Kadoma I, Crandall MD. 2015. Assessing the potential for spunbond, nonwoven biodegradable fabric as mulches for tomato and bell pepper crops. Sci Hortic. 193:209–217. https://doi.org/10.1016/j.scienta.2015.07.019.

Wortman SE, Kadoma I, Crandall MD. 2016. Biodegradable plastic and fabric mulch performance in field and high tunnel cucumber production. HortTechnology. 26(2):148–155. https://doi.org/10.21273/HORTTECH.26.2.148.

Yamoum C, Magaraphan R. 2017. Effect of peanut shell content on mechanical, thermal, and biodegradable properties of peanut shell/polylactic acid biocomposites. Polymer Blends and Composites. 38(4):682–690. https://doi.org/10.1002/pc.23627.

Zero Waste Europe. 2019. El Dorado of Chemical Recycling - State of play and policy challenges. Zero Waste Europe. https://zerowasteeurope.eu/library/el-dorado-of-chemical-recycling-state-of-play-and-policy-challenges/. [accessed 11 Sep 2024].

Zhang H, Flury M, Miles C, Liu H, DeVetter L. 2020. Soil-biodegradable plastic mulches undergo minimal in-soil degradation in a perennial raspberry system after 18 months. Horticulturae. 6(3):47. https://doi.org/10.3390/horticulturae6030047.

Zhang Y, Yin H, Zhao X, Wang W, Du Y, He A, Sun K. 2014. The promoting effects of alginate oligosaccharides on root development in *Oryza sativa* L. mediated by auxin signaling. Carbohydr Polym. 113:446–454. https://doi.org/10.1016/j.carbpol.2014.06.079.