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A Selected Review of Biodegradable Plastics Literature in Agricultural Settings from an Economic and Marketing Perspective

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Contents

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Introduction

The purpose of this document is to review selected research literature on biodegradable plastics in agricultural settings from an economics and marketing perspective. We've organized our study into three sections: the first section provides background on the subject and briefly surveys market issues; the second highlights factors, including evaluation(s) of economic benefits, that influence the preference for biodegradable plastics in general and specifically in agriculture; the third references case studies of their use, including examples of their adoption in agricultural production and agricultural markets in different countries and regions. *Agricultural production* used herein mainly refers to crop production and the improvement of these enterprises through increased water efficiency, weed control, and other means. This may potentially benefit Idaho, a state that produces a substantial and wide variety of crops.

Biodegradable Plastics Industry: A General Background

Plastics are materials that demonstrate flexibility during manufacturing, allowing them to be extruded, molded, cast, spun, or utilized as coatings (Thompson et al. 2009). They are utilized in a variety of industries, including medicine, transportation, manufacturing, sanitation, and agriculture production, including food packaging. As a persistent pollutant that takes a very long time to degrade, however, plastic waste (for example, land-based and ocean-based debris) creates harmful environmental effects, such as the depletion of nonrenewable resources, climate change advancement, and other human and animal health hazards (Mazhandu et al. 2020; Li et al. 2016).

Biodegradable plastics are types of plastics that microbial action converts into carbon dioxide (CO_2), methane, and microbial biomass (Flury and Narayan 2021). They include polylactide (PLA), polyhydroxyalkanoates (PHAs), starch blends, thermoplastic starch (TPS), biobased polycarbonate, and poly butyl succinate (Table 1). Numerous US state governments and administrations in major cities have introduced measures that include regulating terms involving biodegradable plastics.[1] In recent years biodegradable plastics have been widely used in agricultural production (e.g., mulch[2]), making it a promising alternative to conventional plastic mulch.

Table 1. Categories of biodegradable plastics.

	Biobased Plastics		Oil-Based Plastics	
	Derived From Plant-Based Materials	Example of Use	Derived from Crude Oil	Example of Use
Biodegradable Plastics	Poly(lactic acid) (PLA)	Medical	Poly (ἐ-caprolactone) (PCL)	PVC glue
	Polyhydroxyalkanoate (PHA)	Medical	Poly(butylene Succinate/adipate) (PBS/A)	Agriculture
	Polysaccharide derivatives	Food packaging	Poly(butylene adipate-copterephthalate) (PBA/T)	Paper cups
	Poly(amino acid)	Medical		
Non-Biodegradable Plastics	Polyethylene (bio-PE)	Packaging	Polyethylene (PE)	Packaging
	Polyol-polyurethane	Tires	Polypropylene (PP)	Packaging
	Polysaccharide derivatives	Food packaging	Polystyrene (PS)	Packaging
	Poly(ethylene Terephthalate) (bio-PET)	Water bottles	Poly(ethylene terephthalate) (PET)	Water bottles
			Polymethylmethacrylate (Perspex)	Optical materials and others

Adapted from Kjeldsen et al. 2018.

For many market analysts, the biodegradable plastics market offers both opportunities and challenges (for an early discussion, see Mohanty et al. 2002). Lewis (2021), from the United States Department of Agriculture, anticipates a robust growing market. Although biobased bioplastics (i.e., made from renewable sources, for example corn, soybean, or other agricultural feedstock) make up a small part of the traditional plastics market (currently less than 1%), Lewis contends that a 29% growth rate in the 2013–17 bioplastics market and a global-growth expectation of around 18% from 2017 to 2022 makes the biobased industry one of the fastest-growing markets (see also the earlier, extensive study by Golden et al. [2015]). Mazhandu et al. (2020) concur, adding that the global biodegradable plastics market value is expected to increase fourfold by 2027, from US$3.02 billion (2018) to US$12.4 billion. Cision PR Newswire (June 2022) predicts a similar expansion in the US biodegradable plastic market, projecting an increase from US$1.94 billion in 2022 to US$4.85 billion by 2027.[3]

The significant growth in biodegradable plastics market value may be due in large part to increasing demand from the agricultural sector, such as biodegradable packaging for sale of fruits and vegetables at the retail level; or at the agricultural production level, including horticulture, where biodegradable plastic is useful as mulch for conserving soil moisture, reducing the growth of weeds, maintaining favorable soil temperature, and improving soil health, fertility, and aesthetics (Mazhandu et al. 2020). In addition to the industry's healthy bottom line, a robust biodegradable plastics market provides other economic and environmental benefits: the creation of millions of jobs in the United States (Daystar et al. 2021), lower petroleum consumption, less plastic waste, and reduced CO_2 levels.[4]

Considering the quickly expanding and substantial socioeconomic benefit of biodegradable plastics markets, analysts have also increasingly focused on whether—and the extent to which—the presence of biobased material (i.e., renewable or not from fossil fuel material) in products affects consumer intent to purchase (Reinders et al. 2017). Reinders et al. (2017) find that brands using 100% biobased materials (e.g., leaf) received the best appraisal from consumers, thus strengthening their appeal for environmentally concerned consumers. Walter (2011) found that consumers in the United States and Canada were likely to buy biobased products if they know (i) that these benefit the environment (e.g., biodegrade more quickly); (ii) that these are just as effective in their use as the nonbiobased products; and (iii) that these aren't more expensive. Moshood et al. (2022a) reviewed literature regarding the social, economic, and environmental factors affecting the sustainability of biodegradable plastics and found that environmental factors were most critical, followed by economic and social aspects.

A different study investigated the behavior of companies, instead of end consumers, regarding the adoption of biodegradable plastics. For instance, using an empirical survey, Carus et al. (2016) found that most companies were willing to pay an extra price for biobased materials because the use seemed to provide a strategic value to the company (e.g., greened the company's image).

Although biodegradable plastics markets show growing promise, it's worth briefly noting that many issues (e.g., lack of large-scale promotion and applications), threaten to temper the trend. Moshood et al. (2021) specifically enumerate factors that challenge their production (supply), including macroeconomic (e.g., crude oil prices, feedstock costs), regulatory (e.g., taxes, subsidies), technological (e.g., production costs, learning rates), and social (customer awareness and switching intentions) influences (Figure 1). Liu et al. (2021) elaborate further, pointing out that developing and enforcing production standards, lowering production costs, and developing new testing and evaluation systems for plastic biodegradation are necessary responses to the obstacles that lie ahead.

Factors Affecting the Adoption of Biodegradable Plastics

Literature addressing factors that influence these products' adoption generally references two main areas: the willingness to pay (WTP) from consumers (for example, as an end product) and from producers (for example, cost-of-input adoption). In the first case, WTP for biodegradable plastic has been broadly researched. For example, Yue et al. (2010) utilize and compare different econometric models studying conjoint analysis data to elicit floral customers' WTP for biodegradable plant containers. Their results show that participants are willing to pay a price premium (an additional amount) for biodegradable containers, but the premium varies by the type of container. Moreover, with the recent availability of more attractive biodegradable plant containers, increased interest has emerged from the green industry in their suitability as a production input, as well as from end consumers to purchase as end product.

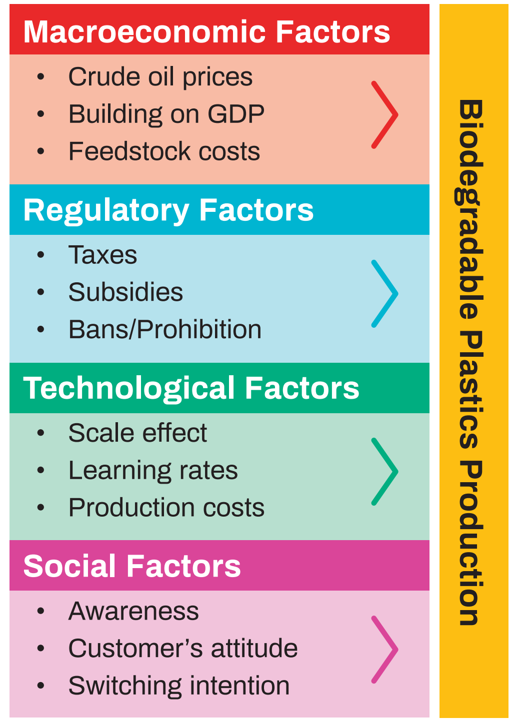

Figure 1. Factors that influence the demand for biodegradable plastics. Adapted from Figure 3, Moshood et al. 2021.

Studies by Kainz (2016) and Kurka and Menrad (2009) found that consumers' awareness of the environmental impact of their behavior increased their WTP for biobased products. Specifically, Kurka and Menrad (2009) interviewed consumers in six European countries about what attributes are important when determining whether or not to buy bioplastic products (Figure 2).[5] They found that ecological motivation seems to have the most influence. Morone et al. (2021) conducted a field experiment in Italy and determined the existence of a "green premium" (increased consumer WTP for biobased products over conventional ones), as well as a "certified green premium" (an additional increase in consumer WTP for certified biobased products over noncertified ones). Using an attitude network approach, Zwicker et al. (2020) found that a perception of guilt—related to environmental issues—drives a higher WTP for biobased plastic products. Similarly, Wensing et al. (2020) tested the effects of green nudges (e.g., nature pictures, reflection questions, etc.) on consumer valuations of biobased plastic packaging, confirming that they increase consumer WTP for these biobased products.

Chen et al. (2020) conducted discrete choice experiments to evaluate the WTP for biodegradable plastic mulch (BDM). They collected data from a survey of stakeholders in the agricultural sector (e.g., farmers, crop advisors, educators, and others) in the Pacific Northwest region of the United States and found that the cost of BDMs is more important to nonfarmers and noncrop advisors, whereas soil health is more of a concern for crop advisors. Cost was significant to other agricultural participants, such as educators and Extension agents, but not necessarily to farmers, who made input decisions based on its effect on profit per unit of crop production. A related study by Velandia et al. (2020) explores the WTP for BDM in the southeastern United States. They obtained a comprehensive list of 990 Tennessee fruit and vegetable farmers from the Tennessee Department of Agriculture and conducted surveys by reaching potential participants via email and snail mail. Their results show that one of the significant factors influencing low BDM adoption is its cost. Their results support the Chen et al. (2020) findings and further indicate that not only price but also on-farm income and familiarity with BDM influence farmer adoption of BDM. Moreover, their results indicate that farmers' WTP for BDM is lower than market prices paid by other users. Very recent

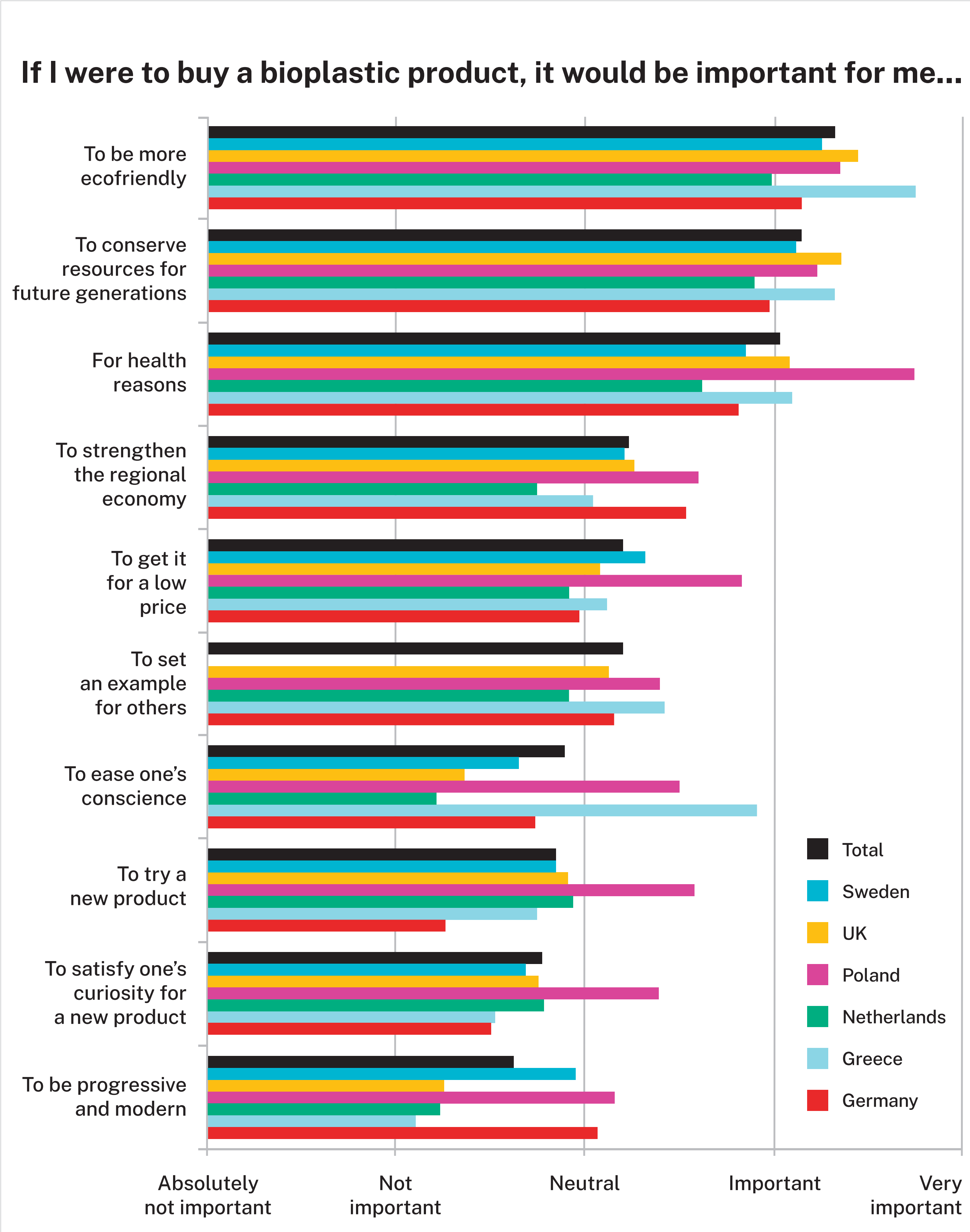

Figure 2. Importance of attributes for consumers purchasing bioplastic products. Adapted from Figure 5, Kurka and Menrad 2009).

research by Moshood et al. (2022b) examines two motivations influencing young consumers—hedonic (e.g., adventurous spirit, novelty seeking) and environmental (environmentally conscious and/or concerned)—regarding the intent to switch from synthetic to biodegradable plastics. They find that both of these motivations favorably impact switching intentions toward biodegradable plastic products.

Other studies indicate additional factors that influence the adoption of biodegradable plastic. For example, Goldberger et al. (2015) note how cost is among the most common barriers to adopting BDM for specialty crop farmers, though insufficient knowledge[6] and experiences of unexpected BDM degradation also discourage use by potential adopters. Velandia et al. (2019) evaluate factors associated with the economic feasibility of adopting BDM in pumpkin production by using partial budgets and conducting sensitivity analyses. Results suggest that the cost of BDM, labor costs, and sale price discounts, due to mulch adhesion in pumpkin fruit, have the greatest impact on profits when transitioning from polyethylene (PE) mulch to BDM.

Biodegradable Plastics Applications in Agriculture

Mulching is a technique widely used in production agriculture that modifies the agricultural soil conditions by covering the surface, totally or partially, with different types of materials (for example, biodegradable plastic, plastic, or tree bark) (Moreno et al. 2017). It provides various benefits for agricultural production. These include weed and insect control (reduces pesticide use, increases soil and air temperature), earlier planting, reduced evaporation and increased water conservation, less soil erosion, and the prevention of soil splashing, increasing crop yield and quality (fruits or vegetables) (Figure 3).

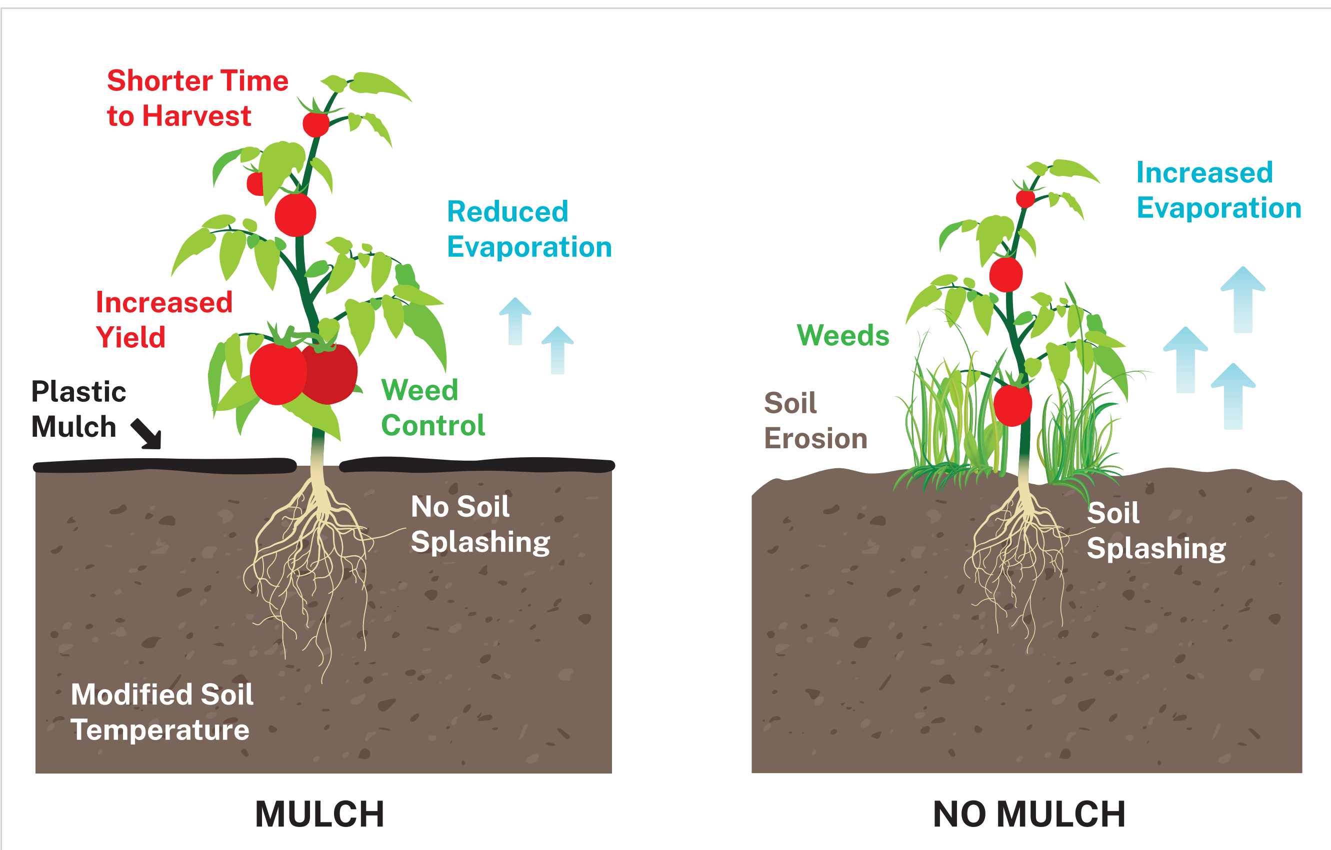

Figure 3. Schematic of agricultural cropping with use of plastic mulch film (left) and without mulch film (right). Adapted from Figure 1, Sintim and Flury 2017.

However, application of plastic or PE mulch can cause substantial environmental problems. The lifetime of PE mulch largely exceeds the duration of crop cycles and, coupled with its difficult removal and subsequent recycling, it is commonly left on the field to be further broken down by successive tillage operations. This in turn generates environmental pollution via steady accumulation of plastics in agricultural soils (Moreno et al. 2017). Improperly disposing of PE materials becomes a significant source of (environmental) pollution, potentially harming life. Moreover, burning polyvinylchloride plastics produces persistent organic pollutants known as furans and dioxins (Jayasekara et al. 2005).

Due to increasing global concerns about plastic pollution, a large variety of biodegradable plastics—for example, BDM film—was developed as potential substitute for PE films (Brodhagen et al. 2017). Agricultural BDM was introduced in the 1980s as an ecological, sustainable alternative to PE mulch (Goldberger et al. 2015). BDMs address plastic environmental concerns and are composed of biodegradable polymers, including polybutylene adipate coterephthalate (PBAT), polybutylene succinate (PBS), and polybutylene succinate-co-adipate (PBSA). These three polymers are typically blended with thermoplastic starch, PLA, PHA, plasticizers, or other additives to improve mechanical properties, like durability or biodegradability. BDMs are intended for sustainable disposal after their field service life by being composted after their (field) retrieval or by biodegradation after their incorporation into soil (Hayes 2021). BDMs, including PHA, poly(propiolactone), and PLA have been broadly used in agricultural production and widely used worldwide (Lambert and Wagner 2017; Urbanek et al. 2020; Sun et al. 2022).

The following economic impact of BDM in agriculture is roughly divided in two parts: on quality and yields, such as crop growth, and on production characteristics (e.g., water efficiency, soil condition, etc.).

Crops

The economic benefits of adopting BDM products (in terms of crop quality, growth, or yields) are roughly similar or in some cases better than from using regular PE mulch, as indicated by numerous studies of usage of different crops grown in different regions. Martín-Closas et al. (2006) conducted a field experiment of organic tomatoes in Spain and found that BDM was a viable or favorable alternative to PE mulch and paper mulch. They found that plant growth, estimated as the total dry weight produced, was similar for treatments with BDM or PE mulch and higher than when using paper mulch as well as for the control variable: bare soil having no type of mulch.

Król-Dyrek and Siwek (2015) conducted a similar study, setting up a three-year experiment to assess the effect of biodegradable mulches on autumn raspberry yields. Results showed that BDM provided a significant increase in the weight of twenty raspberry fruits and higher chlorophyll content in the leaves when compared to the competing control combinations, bare soil and soil with paper mulch. Moreno and Moreno (2008) found that BDM film increased tomato yields in comparison to no mulch (film), at a growing site in central Spain.

A subsequent study by Marí et al. (2019), also in Spain, evaluated the economic profitability of eight BDM materials applied to open-air pepper production. Their results showed higher pepper yields using BDM materials compared to those using PE mulch. Not only in humid regions such as Spain, but also in arid regions like Northwest China, empirical evidence shows that BDM film had a significant improvement effect on crop yields, such as an increase of about 69.4%–76.2% on corn and 65.2%–71.9% on cotton, when compared to bare soil (Deng et al. 2019).

Additional recent studies identified a positive effect of mulch use from biodegradable plastics on crop growth. Zhang et al. (2020a) studied the impact of adopting biodegradable plastic films and its effects on soil temperature and corn yield in northeastern China. Results found that biodegradable plastic film increased the corn yield by 10.4%–14.3% in 2017 and 11.6%–24.7% in 2018. Liu et al. (2021) explored the impact of BDMs on different crops and found that BDMs assist in improving crop yields and water use efficiency. BDM treatments increased corn, wheat, cotton, and potato yields by 26%, 24%, 26%, and 18%, respectively, compared with no mulching treatments. Another recent study by Chen et al. (2021) found that corn yield under PE film mulching and biodegradable film mulching increased by 35.4% and 28.3% compared with no film mulching, respectively.

Environmental Characteristics of Applications

Besides investigating the effect of BDM on crop yields, many studies have examined the effect of BDM on production-setting characteristics such as weed control, water use efficiency, and soil temperature, and the resulting evidence is mixed (Table 2). For example, Cirujeda et al. (2012) conducted a 2006–8 field trial at four locations in Spain, studying weed control during tomato production. Their results show that weed control was high for BDM, paper mulches, and PE mulch, ranging between 80% and 100% in all of them; also, yields were similar for all BDM and paper mulch treatments, ranging between 72% and 108% of the yield achieved by PE mulch.

Evidence from agricultural production in arid regions also show that BDM film effectively increased water use efficiency by crops (corn and cotton), from 64.5% to 73.1% compared to bare soil control (Deng et al. 2019). Zhang et al. (2020b) conducted a two-year field experiment using a newly produced fully biodegradable film in semiarid Kenya in 2016 and 2017 and their results show that BDM proved to be as efficient to save water as PE films did. Similarly, Liu et al. (2021)

Table 2. Study results of environmental improvements of BDM and PE mulch over no mulch.

	Crop(s)	Benefit(s)	BDM	PE mulch
Cirujeda et al. (2012)	Tomato	Weed control	80%–100%	80%–100%
Deng et al. (2019)	Corn; Cotton	Water use efficiency	64.5%–73.1%	64.5%–73.1%
Zhang et al. (2020b)	Corn	Water use efficiency	131.8%	131.8%
Liu et al. (2021)	Corn; Wheat; Cotton; Potato	Water use efficiency	24%; 23%; 15%; 20%	25%; 20%; 20%; 19%
Cowan et al. (2014)	Tomato	Weed control	Significant, similar improvement for BDM and PE mulch (up to 10× less)	
Chen et al. (2021)	Corn	Water use efficiency	35.8%	47.1%
Sintim et al. (2021):	Pumpkin; Green pepper; Corn	Soil aggregate stability	6%–16%	6%–16%
		Water infiltration	10%–12%	10%–12%
Wang et al. (2019)	Cotton	Water use efficiency	Significant improvement; PE mulch better than BDM (up to 1.5×)	
		Soil wet/humidity	Significant improvement; PE mulch better than BDM at boll opening (2×)[1]	
Wang et al. (2021)	Corn	Soil temperature	Significant improvement; daily soil temperature reduction by 1°C–4°C	
		Root morphology	Improved lower (RM) characteristics; clear (colored) mulches over black mulches	

BDM: Biodegradable mulch

PE: Polyethylene

RM: Root morphology

[1] Boll is the rounded, mature fruit of the cotton plant.

show that in comparison to no mulching, under PE mulch treatment the water use efficiency on corn, wheat, cotton, and potato production increased by 25%, 20%, 20%, and 19%, respectively, and, under BDMs treatment, the water use efficiency increased by 24%, 23%, 15%, and 20%, respectively.

Another study by Cowan et al. (2014) compares BDM to PE mulch in tomato production. BDMs performed comparably to PE mulch in weed control, tomato yield, and fruit quality. More importantly, biodegradable polymers improved root growth conditions and fruit quality, showing suitable features for sustainable vegetable production (Sekara et al. 2019). A recent study by Chen et al. (2021) of corn production also shows that water use efficiency increased by 47.1% and 35.8%, respectively, when applying PE mulching and BDMs over no mulching film. In addition, results from Sintim et al. (2021) indicate that BDMs and PE mulch increased the soil aggregate stability by 6%–16% and water infiltration rate by 10%–12% via protecting the soil surface from disturbance when compared to the no-mulch treatment. The reason for this is that BDM containing PBAT/PLA provides equivalent soil-heating properties as PE mulch.

Conversely, some studies involving cotton production indicate that adopting BDM does not result in a favorable difference or may be less effective than conventional PE mulch. That is, PE films resulted in substantial higher water use efficiency than BDM films, which still is an improvement over no mulch. And PE mulch was more effective than BDM films in leaving the soil wet/humid (Wang et al. 2019). This may be attributed to cotton growth being less sensitive to soil salinization during the experimental period. Moreover, soil temperature and root morphology were similar between BDM and PE mulches for a given type of plastic color in corn cropping (Wang et al. 2021). Thus BDM film soil improvements seem to also depend on the particular crop that is being grown.

Conclusion

Companies are increasingly substituting biodegradable plastics for regular plastics, given their environmental and socioeconomic benefits. The industry still faces numerous challenges ahead (e.g., macroeconomic, regulatory, technological, and social factors). However, the market for these products is steadily growing both as a production input and an end product for consumers who seem willing to pay a certain premium for the benefits.

In agriculture, their use is increasing in crop production, specifically biodegradable mulch (BDM) as a substitute for polyethylene (PE) or regular plastic mulch, as well as of paper mulch. Improved crop yields and quality are motivating factors, as well as the environmental benefits accrued from better water use efficiency and weed control, among others. Favorable results from use of BDM varies among crops, soil, and climate conditions, so one size does not fit all. However, the general consensus is that their use provides more benefits than that of regular plastic.

Notes

[1] "Federal, State, and City Regulation," BioBag, https://www.biobagusa.com/about-biobag-2/regulations/.

[2] Mulch is a layer of material applied to the surface of soil that assists in agricultural production (for example in weed control). For more information, see Biodegradable Plastic Application in Agriculture herein.

[3] Cision PR Newswire, "United States Biodegradable Plastics Markets: 2022–2027: Government Focus on Green Procurement Policies and Regulations and Opportunities in the Development of New Applications" (2022), https://www.prnewswire.com/news-releases/united-states-biodegradable-plastic-markets-2022-2027-government-focus-on-green-procurement-policies-and-regulations--opportunities-in-the-development-of-new-applications-301566428.html.

[4] Rinkesh, "Biodegradable Plastics: Advantages, Disadvantages and Various Uses of It," Conserve Energy Future (2023), https://www.conserve-energy-future.com/advantages-disadvantages-uses-biodegradable-plastics.php.

[5] Consumers rated their reactions to different product features by using six categories: "1 = Absolutely not important," "2 = Not important," "3 = Neutral," "4 = Important," "5 = Very important," and "? = Don't know."

[6] Lack of information about an innovation can prevent individuals from moving through the stages in the process of deciding to adopt the innovation.

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