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Synthesis of current evidence on factors influencing the suitability of synthetic biodegradable mulches for agricultural applications: A systematic review

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ABSTRACT

Mulching practice offers farmers an opportunity to minimize the effects of drought, water loss, and soil erosion on crop production. Plastic film is widely used as a mulching material; however, contamination of arable lands by residual plastic has become a serious concern. Synthetic biodegradable mulch films and sprays may offer a more sustainable alternative to plastic films, however current evidence on the factors that influence the suitability of these products for agricultural applications is fragmented, making it unclear under what conditions these products meet agronomic, environmental, and societal needs. We address this gap by conducting a systematic review of studies that evaluate the use of synthesized biodegradable mulch for agricultural applications and extract data from 151 primary studies on factors that directly and indirectly influence the suitability of its use. Like others, we find that using biodegradable mulches nearly always provides agronomic benefits over not mulching but rarely provides agronomic benefits over conventional plastic films. However, we also find that reported benefits vary across climate conditions, mulch type, and crop and agronomic factors tested, highlighting the context-specificity of biodegradable mulch benefits which is not yet well understood. In addition, we identify a need for studies that experimentally evaluate the secondary environmental and social benefits of biodegradable mulch use to provide a better understanding of the full potential of these products for sustainable agriculture.

1. Introduction

The agriculture sector is facing the challenge of feeding a growing population amid global environmental change— two major stressors to food production systems. These stressors will include increased inputs for farming, soil erosion, droughts, floods, wildfires, and heat stress resulting in decreased crop yields [1]. For instance, the U.S. in recent decades has experienced climate events such as droughts and precipitation variabilities, which are projected to intensify to levels where all counties could permanently exceed the baseline variability of occurrence by 2050 under the Representative Concentration Pathway (RCP) 8.5 [2,3]. By the year 2050, it is anticipated that crop yields worldwide will face an average reduction of 10% due to land degradation and climate change, with certain regions potentially experiencing yield reductions of up to 50% [4]. These impacts on agricultural production systems and environmental degradation demand a transition towards more sustainable innovative practices [5,6]. These innovations should broadly contribute to the reduction and reversal of the processes of environmental degradation [7], food security, and soil health through maintaining fertile and functioning soil biodiversity [5,8].

Given the increasing effects of climate change and land degradation on agriculture and soil ecosystems, low-density polyethylene-based mulches (hereafter referred to as plastic mulch) could play a vital role in maintaining soil moisture, retarding soil evaporation, suppressing weeds, and moderating soil temperature in marginal lands areas [3,9,10–12]). These vital roles provide valuable services that reduce irrigation requirements, decrease the use of inorganic herbicide inputs in weed control, and reduce nutrient leaching [13,14]. For example, plastic

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film use has been shown to increase crop yields [15,16], crop quality, and water-use efficiency [17]. In a study by Wu et al. [16], maize yields were 15.2%–23.2% higher under mulching with black plastic film in comparison to a control group without mulching. The same study indicated large differences in mulching effectiveness across mulch types as white transparent plastic film and maize straw mulch resulted in much smaller increases in maize yield over the no-mulch control group [16].

While the usefulness of plastic mulch in agricultural production systems has been identified in literature, plastic mulch materials take a longer period to degrade and are associated with ecologically and agronomically detrimental outcomes. For instance, plastic mulch requires more labor and financial investments for removal and disposal [18–20]. There is an additional cost associated with plastic mulch application due to the cost in waste removal after growing season and disposal fees [21,22]. In addition, micro- or nanoparticles may persist in soil and negatively affect microbial activity, physical soil properties, and nutrient availability [23–25]. As such, biodegradable mulch films are being developed as a sustainable alternative to plastic films and are designed to be integrated into the soil after use where they are degraded by local soil microorganisms [18,26]. Biodegradable mulch films are designed to break down into natural components over time, leaving minimal harmful residues behind and reducing the need for labor-intensive plastic removal after the growing season. The adoption of biodegradable mulch films by farmers has the potential to provide both environmental and economic benefits. Field studies on vegetables (broccoli, chili and garlic) in China showed that biodegradable mulch and plastic mulch provided similar effects on yield, however the biodegradable mulch had more environmental benefits than plastic mulch [15].

Despite its environmentally sustainable prospects, adoption and utilization of biodegradable mulches among farmers are reported to be limited. Among the factors impeding adoption include predictability of degradation rate across local conditions [27,28], desired physical or mechanical properties [29,30], impacts on yields, and effectiveness at preventing weeds or retaining soil moisture [18,22] as well as cost and availability of desired biodegradable mulch types [20,29]. The cost of biodegradable mulch tends to be higher than plastic mulch, and for that reason, net income is lower with biodegradable mulch than with conventional plastic mulch [31,32]. In addition, profitability also depends on climatic conditions [32]. In terms of affordability, Velandia et al. [19] indicated that because biodegradable mulches are more expensive, potential labor savings from the use of biodegradable mulch is important in farmers' assessment of the economic feasibility of replacing plastic mulch. While the number of studies that have specifically focused on the adoption of biodegradable mulch is limited, there are some studies on the factors associated with adoption of sustainable practices in an agricultural context. The general literature suggests little consistency in the factors that are most important determinants of adoption [33]. Some of the more consistent findings in terms of long-term adoption includes farmer's attitudes and preferences, while short-term practice adoption (such as biodegradable mulch) is more related to characteristics of the farm and/or operation [34].

Other factors influencing adoption include a need for evidence of consistent and effective results under various growing conditions as farmers are concerned about the resistance of biodegradable mulches to tearing, degradation, and weed control [27,28], the compatibility of biodegradable mulches with existing farming practices [35], and regulatory barriers and the ambiguity of standardized certification for biodegradable mulch materials [35]. Although research into the degradation rates, agronomic impacts, and adoption of biodegradable mulches is ongoing, there exists limited synthesis of evidence of biodegradable mulch suitability for agricultural applications across studies and sites with varying contexts. Recent reviews and meta-analyses have examined differences in biodegradable mulch production costs and degradation rates [36], mechanisms of polymeric mulch film biodegradation [37], the yield and water use efficiency impacts of biodegradable mulch films in China [10], degradation rates and yield impacts of starch-based biodegradable mulch films [38], and the impacts of different biodegradable mulches on soil temperature, weed suppression, and crop yield relative to bare soil and plastic films [39]. However, there remains a gap in synthesizing how differences in environmental context, mulch type, crop type, and experimental setting interact to influence the overall suitability of biodegradable mulch for agricultural applications. This impedes the ability to effectively identify gaps in biodegradable mulch knowledge, establish evidence for best-practices, and help inform policymakers and producers. Understanding the site suitability and farmers adoption of biodegradable mulch is therefore critical for realizing the full potential of this technology. Given the limited synthesis of current studies on biodegradable mulch suitability and adoption, this review compiles evidence from the literature on.

1. The effects of biodegradable mulch use on agronomic, practice, and economic factors,
2. The effects of biodegradable mulch type and characteristics on agronomic performance and biodegradable mulch degradation,
3. The effects of climate, soil, and other contextual factors on biodegradable mulch degradation and impacts on agronomic performances, and
4. The quality of and confidence in the findings of biodegradable mulch experiments.

Biodegradable mulches impact agronomic factors during both the period of deployment over the cropping season [39] and after being tilled into soil [40]. Evidence shows that biodegradable mulch significantly influences agronomic factors such as soil temperature, soil moisture, weed suppression, and crop yield during deployment [39]. After being tilled-in, Zhang et al. [40] found biodegradable mulch to decrease soil bulk density but increase soil total nutrients and microbial contents in the long-term. In this study, we focus primarily on the agronomic effects of biodegradable mulch and associated contextual factors during the period of deployment unless otherwise indicated. The results of the study will highlight existing and future challenges to this technology that may need to be overcome to facilitate its use for crop production more broadly across the United States and the globe.

2. Methods

To examine the suitability and factors influencing biodegradable mulch adoption, we undertake a systematic literature review focused on this topic. Our approach adheres to the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) standards as established by Moher et al. [41]. In the subsequent sections, we outline our criteria for study inclusion, detail the methodology employed for literature search, discuss the selection process for studies meeting our criteria, and elucidate the coding procedure applied to the collected reports. In this context, we refer to studies that fulfill all our eligibility criteria as selected studies.

2.1. Literature search

The selected publications were obtained from searching commonly used databases, including Scopus, Web of Science, JSTOR, ProQuest, Google Scholar, and Taylor and Francis Online (Table 1). An exported bibliography of 25 sampled relevant studies was used to create search terms and Boolean operators using an iterative procedure in the 'litsearchr' package available in RStudio software [42]. Using common terms extracted from study keywords and titles we obtained and used the following search strings: "biodegradable mulch AND film OR spray AND condition OR suitab*" and "biodegradable mulch AND (film OR spray) AND (condition OR suitab*)", which returned 3333 studies. The

Table 1
Results by database.

Database	Results
Scopus	136
Web of science	162
JSTOR	45
Taylor & Francis online	204
ProQuest (includes dissertation and theses)	1817
Google scholar	969
Total	**3333**

Note: the literature search was concluded on June 15, 2022.

obtained studies included peer-reviewed articles, dissertations, and theses. While we did not restrict publication date or geographical location during our search, we did confine our inquiry to encompass only full-text studies presented in the English language. Our designated search process ended on June 15, 2022.

We note that certain potential limitations should be acknowledged. Though the iterative procedure for search term development enhances comprehensiveness, it might still miss some relevant terms or concepts. Additionally, the reliance on keyword-provided terms from the sampled articles might inadvertently omit key synonyms or related terms. The search strings, although designed to capture a wide spectrum of relevant studies, might still introduce bias due to the specificity of terms used. Furthermore, confining the search to studies available in English could introduce language bias, excluding relevant non-English literature. Lastly, while gray literature sources (dissertations and theses) were sought, the effectiveness of this search strategy in capturing comprehensive and diverse unpublished works could vary. While these limitations do not inherently detract from the significance and practical implications of our findings, it is crucial to recognize that it does impose restrictions on the breadth of our study and the degree to which our results can be generalized.

2.2. Inclusion criteria

Our systematic review seeks to assess the searchable literature on biodegradable mulch evaluation, with the objective of providing a comprehensive summary and synthesis of the state-of-the-knowledge on the factors that impact the suitability of synthesized biodegradable mulch films or sprays for agricultural applications. For a publication to be selected for further examination, it needed to meet the following criteria: 1) full text available, 2) text written in English, 3) studied biodegradable mulch intended for agriculture/crop use, 4) an empirical study and not a review article, 5) focus on synthesized/manufactured biodegradable mulch film or spray, 6) examine biodegradable mulch suitability, and 7) includes field and/or greenhouse trials with soil and plants. See Table 2 for counts of reasons for exclusion.

Table 2
Reasons for publications exclusion in Step I and Step II.

Reasons for Exclusion	Number of Publications Excluded	
	Step I	Step II
Not topical	1867	22
Review article	298	21
Suitability not examined	23	11
Not agricultural	136	5
Not in English	16	13
No full text	152	–
Only lab experiments	–	38
Not manufactured biodegradable mulch	–	35
Conventional plastic only	–	12
No field or greenhouse trials with soils/plants	–	11
Two or more of the above reasons	–	90
Other	–	19
Total	**2492**	**277**

Note: the literature search was concluded on June 15, 2022.

Note that we include studies that involve human surveys or interviews if there is some associated application of the product to crops (e.g., inviting farmers to observe field trials and then getting farmers opinions on biodegradable mulch suitability for crop production and factors like cost that are associated with those opinions). A study was considered to examine the suitability of biodegradable mulch if it examined attributes of a biodegradable mulch film or spray that included (but were not limited to): degradation, physical properties, impact on soils, water, weeds, crops, production, farm management, or application feasibility.

2.3. Studies meeting eligibility criteria

To ensure that the quality of the studies included in the review met the set eligibility criteria for inclusion (Table 2), we used a three-step process to screen and code selected studies that met all the eligibility criteria (Fig. 1). In step one, unique studies identified in the database search were screened using title and abstract in the 'revtools' R package [43]. Pairs of coders independently determined if the title and abstract of each study met the inclusion criteria. A total of 2920 unique publication records were screened for title and abstract suitability. Following the independent evaluation, pairs of coders checked for conflicting inclusion decisions and shared their reasons for including or excluding studies. In the case of continued disagreement on exclusion across a coding pair a third author resolved discrepancies and disagreements. Most of the excluded studies did not examine topics relevant to biodegradable mulch for agriculture application [44–46] or did not involve field studies or experiments ([47,48]; W [49]). In all, 2492 studies were excluded under step one (Table 2).

In step two, 428 studies were evaluated for inclusion using a full text reading. We uploaded PDF files of the 428 studies for full text screening in SysRev.com [50]. We coded exclusion and reasons for exclusion in the form of labels to help screen the studies in SysRev. Pairs of reviewers independently assessed whether each study fit the eligibility criteria. The SysRev project was set to randomly assign a study to two reviewers with each blinded from seeing the screened results and the assigned reasons for exclusion of others. This allowed the SysRev system to mark a study as completed if there was no conflicting review label or as conflict if the two reviewers' labels lacked consensus. A third reviewer

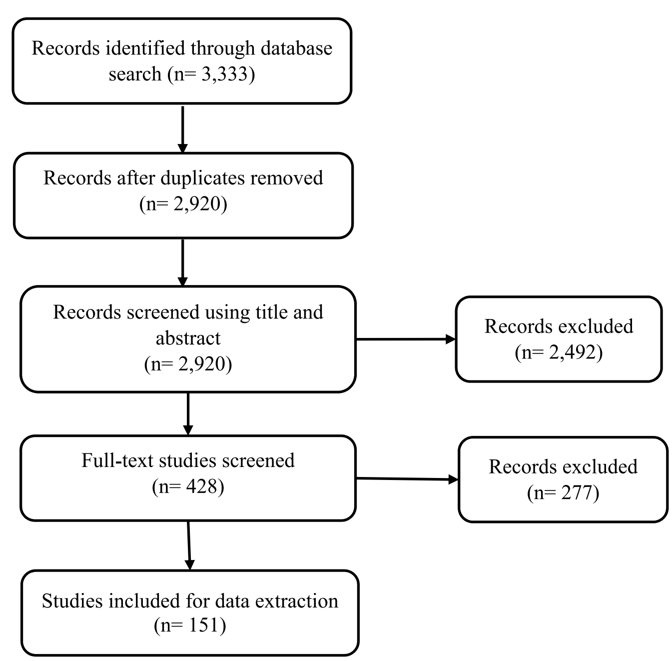

Fig. 1. Flow chart of the systematic review process with study counts. ***Note:*** *the literature search was concluded on June 15, 2022.*

resolved disagreements between paired reviewers. We excluded 277 studies using the full text review under step two. Thus, 151 studies were selected for data extraction after the full-text screening (See SI Table 2). For both screening steps, a reviewer training session was held before conducting a pilot screening of ten studies for step one and five studies for step two. A post pilot discussion was used to address procedural questions and inconsistencies in inclusion/exclusion decisions.

From the full text reviewed studies, common reasons for excluding studies included lack of biodegradable mulch experiments with soil and plants in a field or greenhouse setting, use of naturally-occurring rather than synthesized biodegradable mulch products, and non-topical or review studies. For example, Verdú et al. [51] and Okyay et al. [52] studied biodegradable mulch effects on agronomic factors, but the studies were excluded as the authors conducted the research only in controlled laboratory conditions. Similarly, Marral et al. [53] evaluated effects of biodegradable mulches on soil properties, weed dynamics and yield of winter crops, however while the implications of biodegradable mulch suitability for agriculture application were discussed the study was excluded because the authors used cotton mulches which are not synthesized or manufactured. On the other hand, a study by Cirujeda et al. [54] was retained for further analysis as they examine the effect of a manufactured biodegradable paper mulch on weed control in field experiments with tomatoes. Although Rudnik & Briassoulis [55] examined the suitability of biodegradable mulch for agriculture applications in field trials, the study was excluded because the researchers did not involve crops or plants. Lastly, a study by Qin et al. [49] was excluded as it was a review paper and did not specifically focus on biodegradable mulch for agricultural use.

2.4. Data extraction and coding report

In step three, data were extracted from the selected studies using SysRev [50]. We coded the questions in the form of labels to help guide data extraction. Labels included opened ended questions (string labels) and closed ended questions (categorical labels). Coding (data extraction) instructions and help guides (for reviewer's reference) were provided for each label as well as in the SysRev project description. All coders were trained on how and what data to extract from the studies and practiced this data extraction in a pilot screening exercise (using five sample studies). After training, pairs of coders independently extracted relevant information from each of the remaining 151 studies using the created labels schema (See SI Table 1). The SysRev project was set to randomly assign every study to two coders with each blinded from seeing the data extracted by others. The SysRev system marked a study as completed if there was no conflicting label or as conflict if the two coders' labels lacked consensus. A third reviewer resolved conflicts between labels for paired reviewers.

Key information extracted includes the study location, type of crop, research setting, and the characteristics and type of biodegradable mulch used in the study. Other extracted information includes, biodegradable mulch physical properties evaluated, agronomic impacts/factors (i.e., yield, soil temperature, etc.) studied, studied contextual factors that may influence biodegradable suitability, and the reported effectiveness of biodegradable mulch compared to bare ground and plastic mulch controls. For more information, see Appendix SI Table 1.

2.5. Data cleaning and analysis

The extracted data in the SysRev project was downloaded in. CSV file format and then imported, cleaned, and processed in RStudio. Ancillary information, such as world biome types (a community of plants and animals living together in a certain kind of climate), country subregional groups, and crop groups were added to aid in further data classification and consolidation. Biomes were added to help assess the variability in the effectiveness of biodegradable mulch across different ecological regions [56]. Subregional divisions from the United Nations Statistics Division [57] were added to examine variability of biodegradable mulch uses and its effectiveness across collections of countries. The crop groups were adopted from the United States Department of Agriculture and Natural Resources Conservation Service U.S. National Vegetation Classification [58] to reduce the number of unique crop categories analyzed. As many studies report multiple trials and experiments [e.g., Anunciado et al. [59] use three crops (i.e., corn, pepper, and pumpkin) in their study and Briassoulis [30] studied biodegradable mulch suitability in four different countries including Italy, Greece, France, and Germany] for which we were able to extract trial-specific data we report the frequency of individual factors across the primary studies using the count of unique observations per paper. Note, however, that agronomic impact measures extracted from the primary studies were not recorded for individual trials described in a study. The category "positive impact" was only applied if all trials with biodegradable mulch were reported to have positive impacts relative to the comparison group (no-mulch control or conventional plastic). The neutral category was applied if the study consistently reported no significant difference between impacts of biodegradable mulch use and the comparison group while the mixed category was applied if the study reported positive impacts of biodegradable mulch relative to the comparison group for some trials and negative impacts for other trials. Data extracted as unique text strings were recategorized using common themes and terms.

3. Results

3.1. Study area and publication statistics

The data comprises studies conducted in 24 countries across diverse farming regions in the world. Studies in the United States, Canada, and Italy were early leaders in the field, with studies starting in 1996–2002, but account for only 3.97% of the selected studies. In contrast, about 29.8% (45 studies) of the selected studies were conducted in locations within China with publication dates between 2005 and 2022 (Fig. 2). Since 2009, there has also been growth in biodegradable mulch studies in Central and South America, with five (5) studies conducted across Brazil, Costa Rica, Mexico, and Ecuador (Fig. 2). The recent growth in research on biodegradable mulch (Fig. 3) may be associated with an increase in efforts to protect crops against climate change and replace plastic mulching materials [18].

3.2. Study setting and crops of study

A large proportion (80.1%) of the selected studies were conducted in field settings (on farmland) involving different crops and soil (Fig. 4, SI Fig. 1). Moreover, all the agronomic factors considered were tested under field conditions in at least one study. The most studied agronomic factor under field conditions was effect on crop yield, representing 72.5% of the total field studies, while pest and disease control were the least studied.

The results suggest that biodegradable mulch application has been tested for a diverse range of crops and farming systems. Over 37 different types of crops have been used to evaluate biodegradable mulch suitability for agricultural applications (SI Table 3). Among the most studied crop groups is the Forb row crops (as shown in Fig. 5). This group encompasses a variety of crop types, including Pie pumpkin, Cotton, Lettuce, Watermelon, Potato, Broccoli, and Peppers (refer to SI Table 3). Corn/maize was the most frequently studied individual crop as it was used in 19.2% (28 studies) of the total studies (SI Table 3).

In terms of differences in the studied crops by country, the Forb row crop group was the most common among studies conducted in the USA and Australia (Fig. 6). For example, the effectiveness of biodegradable mulch has been assessed with crops such as Pie pumpkin, watermelon, and pepper in USA [19,59,60], and cotton in Australia [61]. The Graminoid row crops were the main crops used in studies conducted in China. On the other hand, Bush fruits & berry crop group emerged as the

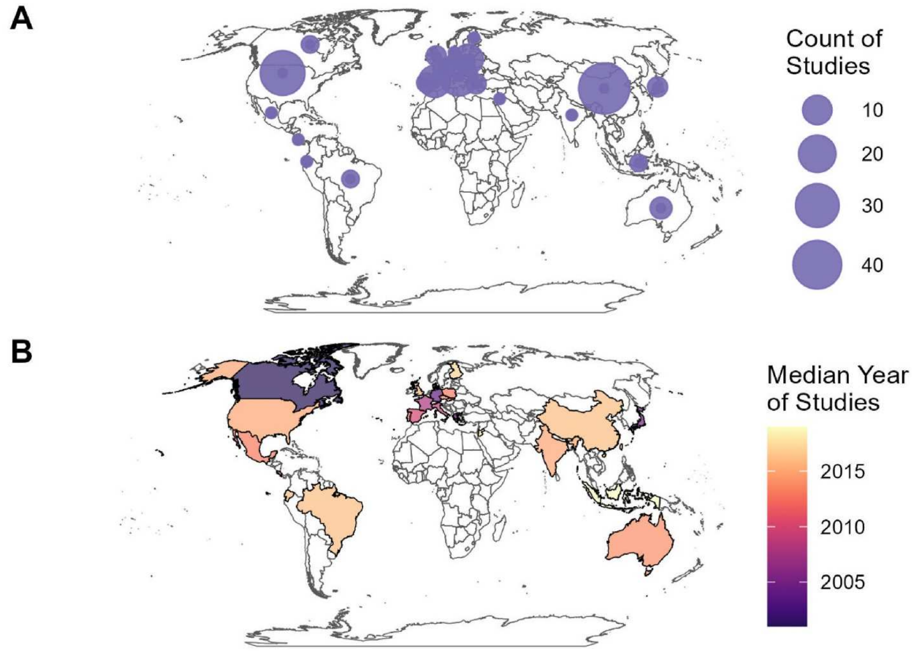

Fig. 2. Spatial distribution of publication counts (A) and median publication year (B) by country of study. ***Note:*** *the literature search was concluded on June 15, 2022.*

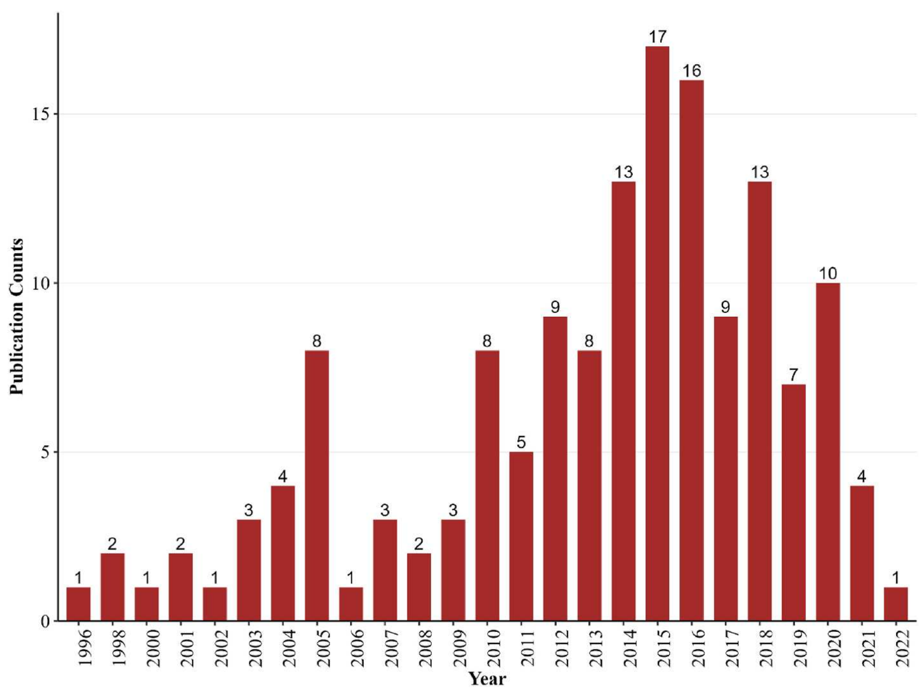

Fig. 3. Publication counts by year of study.

predominant crop type among the European countries.

3.3. Biodegradable mulch

3.3.1. Studied biodegradable mulches

The primary studies used a wide variety of biodegradable mulches, that can be broadly classified into 14 categories of mulches (Table 3). The primary studies typically report and identify the tested mulches using commercial names, the main constituent of a polymer blend, or through alternative application formats. The most frequently studied mulches, identified via the main polymer blend include Polylactic acid (PLA), Polybutyrate adipate terephthalate (PBAT), and starch-based mulches. While the most commonly studied mulches identified via commercial name were Mater-Bi® and Bionolle nonwoven mulches (Table 3). Studies reporting to have used Mater-Bi®-based mulches were predominantly associated with experiments on tomato crops [62,63,54]. We further observed that Mater-Bi®-based mulch was frequently used in studies conducted in European countries such as Italy, Spain, and Poland, where tomatoes are widely employed in mulch experiments (see SI Fig. 1 and SI Table 4).

Studies investigating mulch effects on Pie pumpkin mainly utilized PLA- and PHA-based mulches [64–66]. This trend is largely attributed to

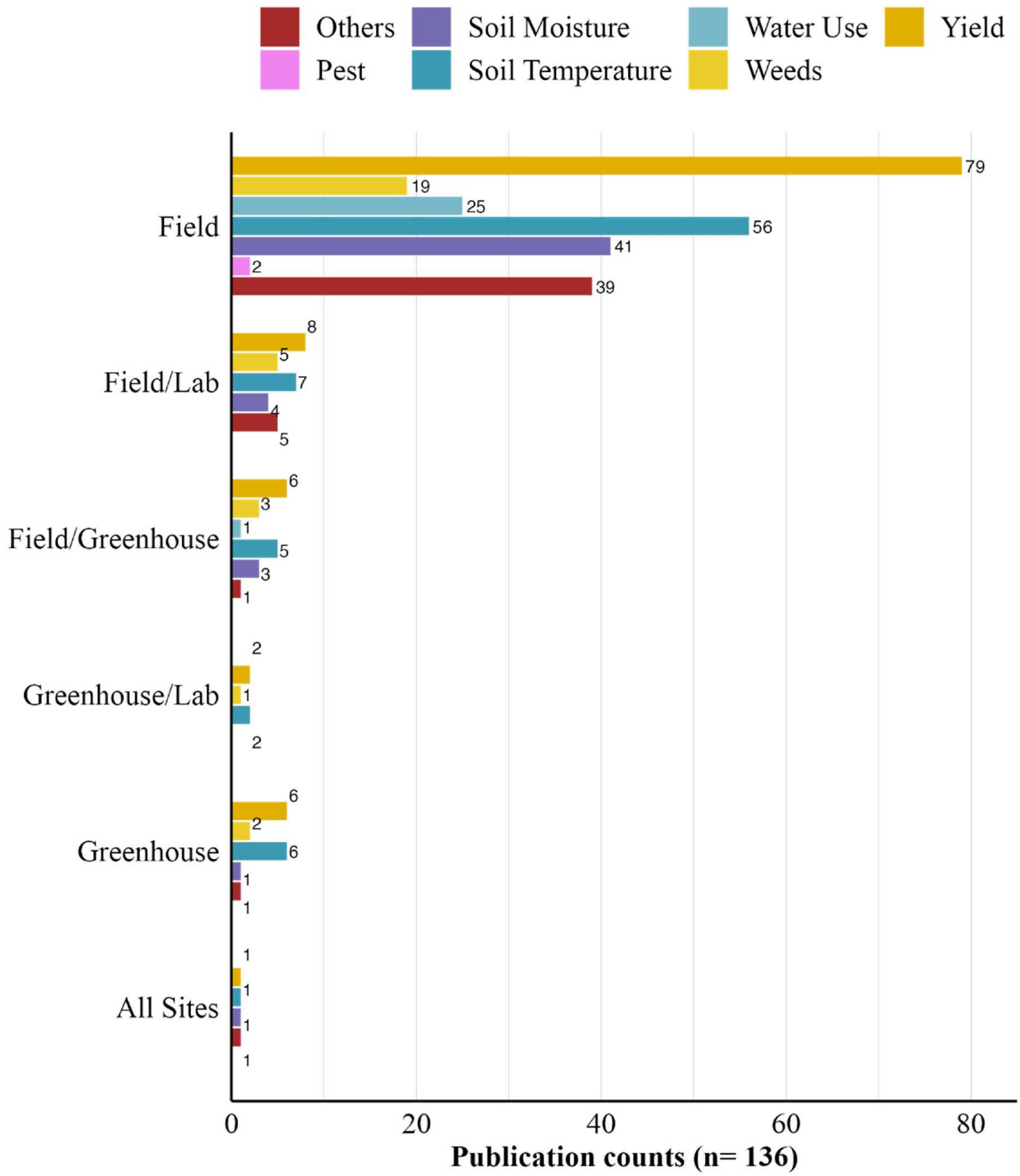

Fig. 4. Study setting and agronomic impacts studied. **Note:** *Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on other agronomic factors [Others].*

the fact that almost all the studies involving Pie pumpkin originate from the USA, where these mulches are also commonly studied (refer to Fig. 6, SI Fig. 1, and SI Table 4). In terms of assessing the suitability of mulches in row crops such as corn and wheat, the predominant polymer blend mulches used were PBAT, PLA, and PHA mulches [67,59,68].

3.3.2. *Physical properties of biodegradable films*

Most biodegradable mulches are designed to be applied in similar fashion as conventional plastic mulches, but then tilled into the soil after use, eliminating waste and disposal challenges [12,14]. To achieve this aim, biodegradable mulches are expected to have certain physical and mechanical properties comparable to conventional plastic mulch in addition to being biodegradable [69,70,71]. As such, research has often examined the physical and mechanical properties of biodegradable mulch to assess its compliance with standard requirements, suitability for agricultural applications, and to identify properties appropriate for specific crops, climates, and farming practices. The common properties of concern for practical use include tensile strength, elongation at break, thickness, water permeability, degradation rate, UV resistance, as well as color and light reflectance. Others included porosity, puncture resistance, and adhesion strength.

About 87% of the studies that considered physical properties of biodegradable mulches examined the degradation rate (Fig. 7), which is essential to understanding the mulch's lifespan and its environmental impact. The studies measured degradation rate as an indicator of how quickly the mulch breaks down into natural components over time

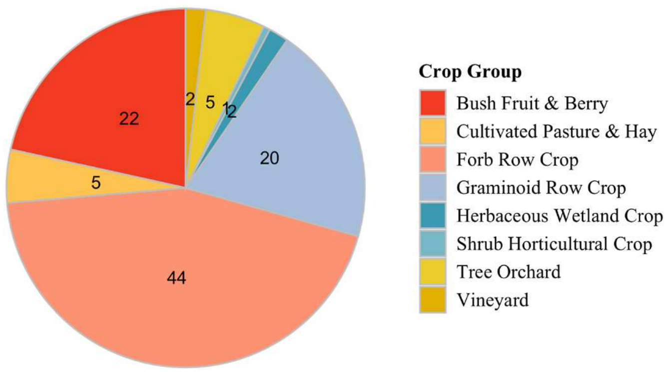

Fig. 5. Types of crops and crop groups used in biodegradable mulch studies (figures in percentages). **Note:** *Forb Row Crop [Forb Crop], Tree Orchard, Bush Fruit & Berry [Bush Fruit], Cultivated Pasture & Hay [Pasture & Hay], Graminoid Row Crop [Graminoid Crop], Herbaceous Wetland Crop [Wetland Crop], Shrub Horticultural Crop [Horticultural Crop], Vineyard.*

during deployment and or after being tilled into the soil [72,73]. While several studies [66,74] examined degradation rate of tilled-in mulch beyond the growing season or over multiple growing seasons, the majority of the primary studies examined degradation only during the deployment period. Degradation was often evaluated qualitatively based on physical appearance through periodic inspection of the mulch during deployment for visible signs of degradation, such as changes in color, texture, or the presence of holes and cracks ([75]; C [76]). Relatedly, mulch degradation rate during deployment was sometimes assessed through the percent soil exposure technique [59], where 0% represented soil that is completely covered by mulch and 100% represented fully exposed soil [77]. The reported field trial degradation rate during the deployment period often ranges from 10% to 96% within a period of 60 days (about 2 months) to 120 days (about 4 months) [66,78,79,59].

Over 43% of studies that evaluate physical properties assessed biodegradable mulch tensile strength while 31% examined thickness and suitability for agriculture application (Fig. 7). Assessment of tensile strength is critical to ascertaining the mulch's durability during installation, exposure to environmental factors, and resistance to tearing [80,81]. The level of thickness influences the mulch effects on agronomic factors such as moisture retention and weed suppression and could vary depending on cost and the intended application (See Table 5). Reported thickness is generally within the range of 0.015 mm–4 mm [81,82]. Other properties such as much color and ultraviolet (UV) resistance were also examined by 8% of the studies. Dark-colored mulches can absorb more heat, potentially increasing soil temperature, while reflective mulches can help maintain cooler soil temperatures [83,84]. UV resistance measures how well the mulch can withstand exposure to UV radiation from sunlight without degrading or becoming brittle [85].

Whereas the amount of sprayable mulch applied (i.e., layer thickness) is noted for influencing crop yields, soil health, and weed control, we found that only two out of the 20 studies considering sprayable mulch empirically assessed the amount of the mulch applied (Fig. 7). For example, Khan et al. [86] found that the amount of sprayable mulch applied with herbicides shapes its effects on weed control. Similarly, Giaccone et al. [87] found that inadequate sprayable mulch application or coverage may leave gaps where weeds can emerge, reducing the effectiveness of weed suppression. Excess mulch application contributes to residue pollution if not fully biodegraded, while insufficient mulch can result in increased herbicide use to control weeds [86,88].

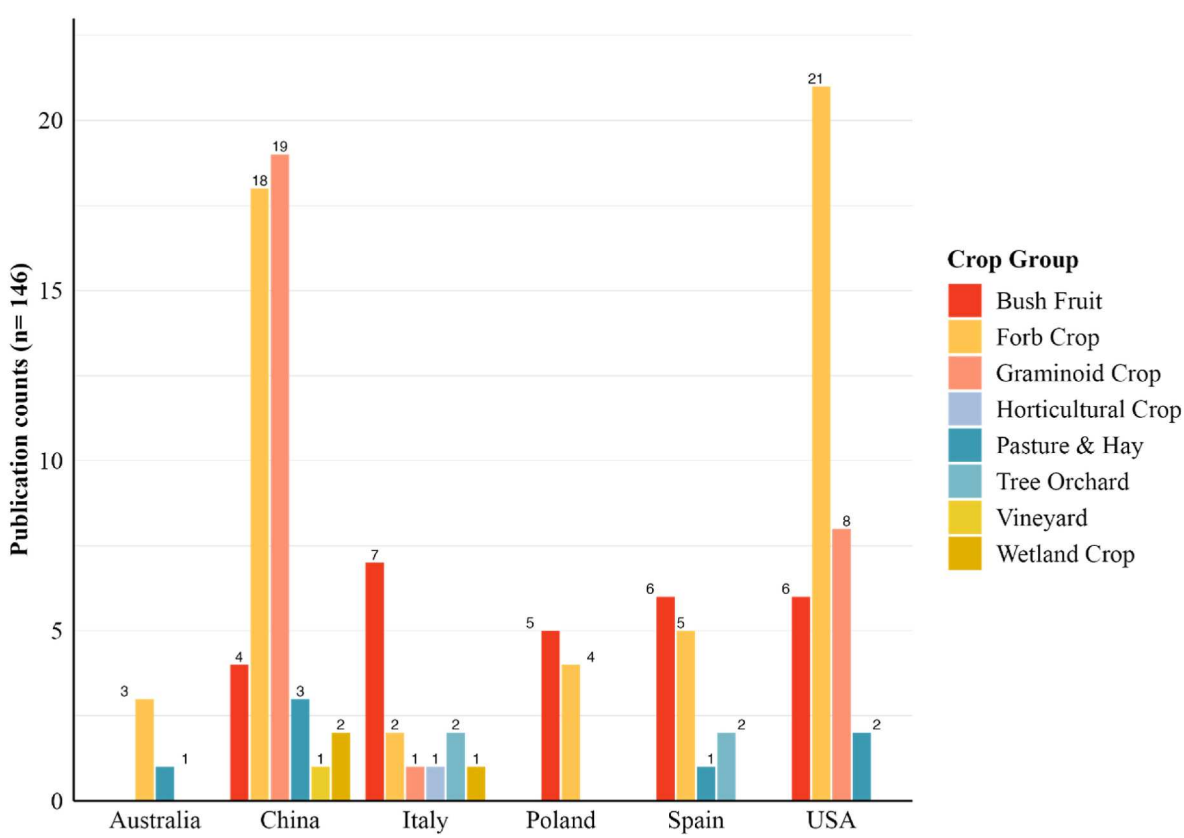

Fig. 6. Crop groups and country of study. **Note:** *Forb Row Crop [Forb Crop], Tree Orchard, Bush Fruit & Berry [Bush Fruit], Cultivated Pasture & Hay [Pasture & Hay], Graminoid Row Crop [Graminoid Crop], Herbaceous Wetland Crop [Wetland Crop], Shrub Horticultural Crop [Horticultural Crop], Vineyard.*

Table 3
Studied biodegradable mulches.

Studied mulches	Percent of studies (%)
Mulch identified by commercial/trade names	
Mater-Bi®/Mater-Bi™/BioAgri of Mater-Bi® (Mater-Bi)	13.2
Biodegradable plastic Bioflex (BPB)	1.3
Biodegradable plastic Ecovio (BPE)	1.3
Bionolle biodegradable nonwoven (BBN)	2.6
Mulch identified by main polymer blends	
Polylactic acid (PLA)	19.2
Polybutyrate adipate terephthalate (PBAT)	17.9
Polybutylene succinate and adipate (PBSA)	5.3
starch-based biodegradable film (BDF)	10.6
Polyhydroxy-alkanoates (PHA)	7.3
Cellulose-based biodegradable film (CBF)	2.6
Ethylene vinyl acetate (EVA)	1.3
Polyvinyl alcohol (PVA)	5.3
Mulch identified by alternative format	
Sprayable biodegradable mulch film (BSM)/Liquid film (LF)	6.6
Biodegradable paper mulches (BPM)	13.2

Note: *The specific content of each polymer blend is not reported in all studies.*

3.4. Study agronomic impacts

Effects of biodegradable mulch on crops yields was the most studied agronomic factor, constituting about 102 studies out of a total 136 studies examining suitability in terms of agronomic impacts (Table 4). For example, earlier studies such as Shogren & Hochmuth [60] evaluated the effects of biodegradable mulch application on watermelon yields in the field compared to plastic mulch. More recent studies including Qiao et al. [68] and Shine [89] assessed the effects of biodegradable mulch on the yield of cereal crops such as corn, wheat, and rice production. The focus of most research publications on the effects on crop yields, as opposed to other agronomic factors, could be due in part because other agronomic impacts ultimately contribute to the end goal of crop yields. We found a sufficient research interest on biodegradable mulches' effect on soil temperature, soil moisture, weed control, and water use efficiency (Table 4). The least studied agronomic factor was impact of biodegradable mulch application on pest and disease control, with only a total of two (2) studies. Other agronomic factors examined include biodegradable mulch application effects on crop growth, soil microbes, soil nutrients, crop quality, cost and economic benefits, and germination rate.

The focus of each study on specific agronomic factors varies based on the objectives of the studies, research priorities, and the specific region of study. All agronomic factors are analyzed at multiple sub-regions, and studies from all the sub-regions examined multiple agronomic factors (Fig. 8). However, we noticed a larger fraction of studies focusing on crop yields in regions with highly developed countries where large-scale industrial agriculture is predominant. Some of the sub-regions and countries where research on the effects of biodegradable mulch on crop yields is particularly prominent include: (i) Eastern Asia (China and Japan have a significant focus on agricultural productivity and interest in sustainable practices, including biodegradable mulch (Fig. 2)), (ii) North America (the United States and Canada have robust agricultural research with a substantial focus on biodegradable mulch and its impact on crop yields), (iii) Southern, Northern, and Eastern Europe (European countries are at the forefront of sustainable agriculture practices, and biodegradable mulch research is common in countries like Italy, Spain, and Poland (Fig. 6)). The choice of agronomic factors to study was also dependent on local climate conditions. For example, sub-regions Central/South America, Eastern Asia, and Australasia with hot summers and humid conditions had a relatively higher frequency of studies focusing on biodegradable mulch effects on soil temperature and moisture retention (Fig. 8).

The assessment of biodegradable mulch effects was mainly conducted through analysis of variance using one-way ANOVA to test the differences between biodegradable mulch and control effects [90]. Among the studies evaluating biodegradable mulch effects on crop yields (Fig. 9), over 83.9% reported an increase in crop yields (positive) when using biodegradable mulch compared to bare soil [91–93], while only 15.6% indicated an increase in yield compared to plastic mulch [94,95]. Moreover, about 5.7% of the studies found no significant yield differences (neutral) between crops grown under biodegradable mulch and bare soil, while 28.6% observed no significant yield differences compared to plastic mulch [61,96]. Similarly, 9.2% of the studies reported mixed findings (i.e., both positive and negative differences) on yield differences compared to bare soil [97,98], while over 27.3%

Table 4
Studied agronomic factors.

Agronomic factors	No. Of studies
Effect on crop yield	102
Effect on soil temperature	77
Effect on soil moisture	50
Effect on weed control	30
Effect on water use efficiency	26
Effect on pest and diseases	2
Effect on crop growth	17
Effect on soil microbes	11
Effect on soil nutrients	6
Effect on crop quality	19
Effect on cost and economic benefits	8
Effect on germination rate	3

Note: the literature search was concluded on June 15, 2022.

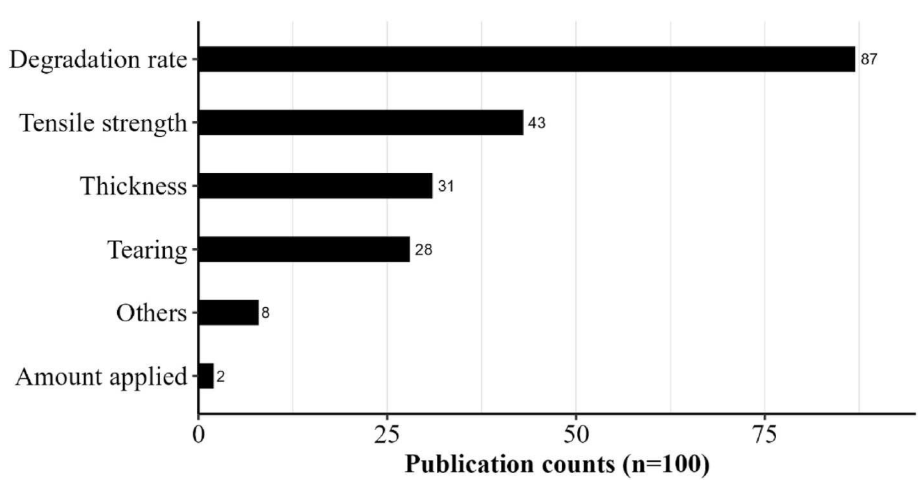

Fig. 7. Studied biodegradable mulch mechanical properties.

Table 5
Synthesis of contextual factors influencing mulch suitability or effectiveness.

[a]Agronomic factors	Contextual factors	Influence of contextual factors
Crop yield	1. Mulch color 2. Mulch thickness 3. Ambient temperature 4. Precipitation/rainfall 5. Solar radiation 6. Soil microbes 7. Soil pH level 8. Crop/vegetation cover	1. White transparent films are more effective in increasing soil temperature and early crop maturity. 2. Thicker mulches (i.e., at least 15 mm) degrade slower and maintain their functionality throughout the growing season. 3. Higher atmospheric and soil temperatures cause cracks and rapid degradation of mulch before the end of the desired coverage period, thereby reducing its effectiveness. 4. Excess rainfall causes disintegration and rapid degradation of mulch before the desired coverage period, which reduces its effectiveness. 5. Higher solar radiance causes disintegration and rapid degradation of mulch, which reduces its effectiveness. 6. The presence of certain soil microbes facilitates the mulch degradation process. 7. The presence of a certain range of soil pH creates a conducive environment for the rapid disintegration of mulches. 8. Mulch applied under crop or vegetation shade was more effective due to reduced contact with direct solar radiation.
Weed control	1. Mulch color 2. Mulch tensile strength 3. Weeds species 4. Crop/vegetation cover 5. Stage of application	1. Black films are more effective in controlling weeds through sunlight exclusion. 2. Mulch with lower tearing and tensile strength is likely to develop cracks and wear allowing weeds to germinate and penetrate through. 3. Nutsedges (Cyperus spp.) and other weeds with sharp growing points can lift mulch films or puncture and emerge through the film. 4. Mulches were more effective in weed control under vegetation or crop canopy due to enhanced blocking of sunlight reaching the mulch and soil surface. 5. Mulch application at the early stage of crop planting is more effective in weed control.
Water use efficiency	1. Mulch tensile strength 2. Field level practices	1. Mulch with higher tearing and tensile strength is likely to maintain its functionality throughout the growing season, and therefore prevent runoff or provide soil more time to absorb rainwater by lowering the kinetic energy of rain or by slowing the movement of rainwater, which enhances root water absorption. 2. Crop soil water use and runoff efficiency increased with wider ridge width. 3. Mulch application in furrow ridge irrigation reduces amount of irrigation water demand.
Soil temperature	1. Mulch color 2. Ambient temperature	1. White transparent and infrared-transmitting films allow solar radiation to reach the soil and are more effective in increasing soil temperature.
Soil moisture	1. Mulch thickness 2. Mulch tensile strength 3. Types of soil texture 4. Ambient temperature 5. Precipitation/rainfall	1. Thicker mulch reduces soil water evaporation and is more effective in soil water retention. 2. Mulch with lower tearing and tensile strength is likely to develop cracks and wear resulting in soil water evaporating through those cracks.
Pest and disease control	1. Mulch color	1. White transparent films reflect radiation to help control the presence of some insect pests.
Crop growth	1. The stage of crop growth at which the mulch is applied	1. Mulch application at the early stages of crop growth were more effective than at later stages of crop growth.

[a] **Note**: *Only the effect of biodegradable mulch during deployment over the cropping season.*

studies observed mixed results on yield differences compared to plastic mulch [88,99]. The mixed results were partly due to the use of multiple biodegradable mulches in a single study, differing impacts across treatment replicates, or early degradation of the mulch before the end of the growing season leading to differing impacts throughout the course of experiments.

The reported relative benefits of biodegradable mulch varied strongly for weed control, soil temperature, and soil moisture (Fig. 9). Thus, while a vast majority (96.2%) of the studies observed that biodegradable mulch controlled weeds more effectively (positive) than no-mulch [100,101], only 15.8% found the mulch to have controlled weeds better than plastic mulch [102]. In terms of soil temperature, 80.9% of studies found soil under biodegradable mulches to have higher temperature (positive) compared to bare soil [92,93,99], while 8.9% studies reported a rise in soil temperature compared to plastic mulch [78]. Conversely, 5.9% of studies observed lower temperature (negative) of soil under biodegradable mulch compared to bare soil [103,104], while over 46.4% observed a decreased soil temperature compared to plastic mulch [82,105]. Relatedly, a greater proportion (89.1%) of the studies found that biodegradable mulch increased or retained soil moisture (positive) relative to bare soil [73,106], while only 7.1% found an increased in soil moisture content compared to plastic mulch [107].

There was no noticeable disproportionate reporting of positive results for agronomic effects from specific countries' sub-regional groups (SI Fig. 3 and SI Fig. 4) other than for regions located in hot climate conditions (Australia and Central/South America), where very few negative effects were reported (SI Fig. 3). Thus, it was observed that studies conducted in global biomes with hot summer, arid, and or humid climate conditions [108,109], were more likely to report positive effects of biodegradable mulch application irrespective of the agronomic factor being assessed (SI Fig. 5). For example, studies in the temperate broadleaf & mixed forests biome reported neutral to positive effects of biodegradable mulch in 90.9% cases in comparison to no-mulch and in 48.8% of cases relative to plastic mulch treatment, which is higher than performance in any other biome. Also, the desert shrublands and Montane grasslands reported 100% positive effects of biodegradable mulch compared to bare soil. These results may be indicative of a greater suitability of biodegradable mulch in arid hot climate regions.

Generally, agronomic impacts relative to no-mulch were reported as positive in the vast majority of cases for all mulch types (SI Fig. 7).

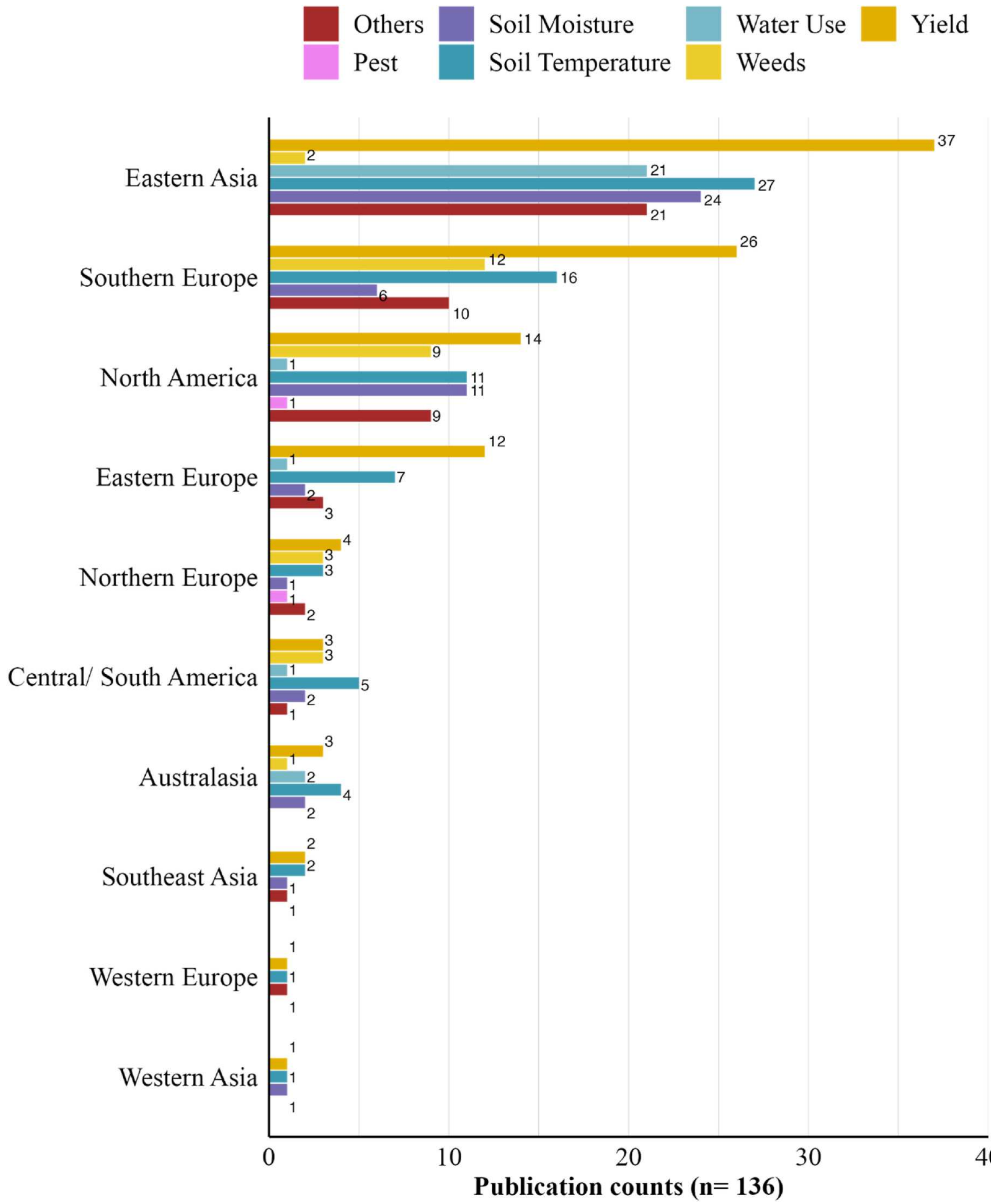

Fig. 8. Studied agronomic factors across sub-regional divisions. **Note:** *Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on other agronomic factors [Others].*

Mater-Bi®-based mulch products and paper mulch products tended to show the most comparable or positive impacts relative to plastic mulch, with paper mulches outperforming other mulch types for weed control and Mater-Bi®-based mulch outperforming other mulch types for yield. On the other hand, polybutyrate-based products, which were most frequently tested in experiments in China, tended to show more negative results when compared with plastic, particularly for soil moisture retention, however all mulch types displayed a high degree of variability in findings (Fig SI 8).

The comparative effects of biodegradable mulches differ across the crop groups (SI Fig. 9 and SI Fig. 10). The relative effects of biodegradable mulches across different crop groups show varying positive benefits compared to no-mulching, with Graminoid, Forb, and Bush Fruits reporting a higher frequency of positive effects (96.6%, 82.0%, and 78.7% of instances, respectively) regardless of agronomic factor (SI Fig. 9). However, all crop groups recorded fewer positive effects when compared to plastic mulch, with benefits most frequently observed for Bush Fruits (17.0%), Graminoid (15.7%), and Forb (8.5%) crop groups. In terms of crop yields, all groups except for the Vineyard group showed increased yields under biodegradable mulching, with Wetland,

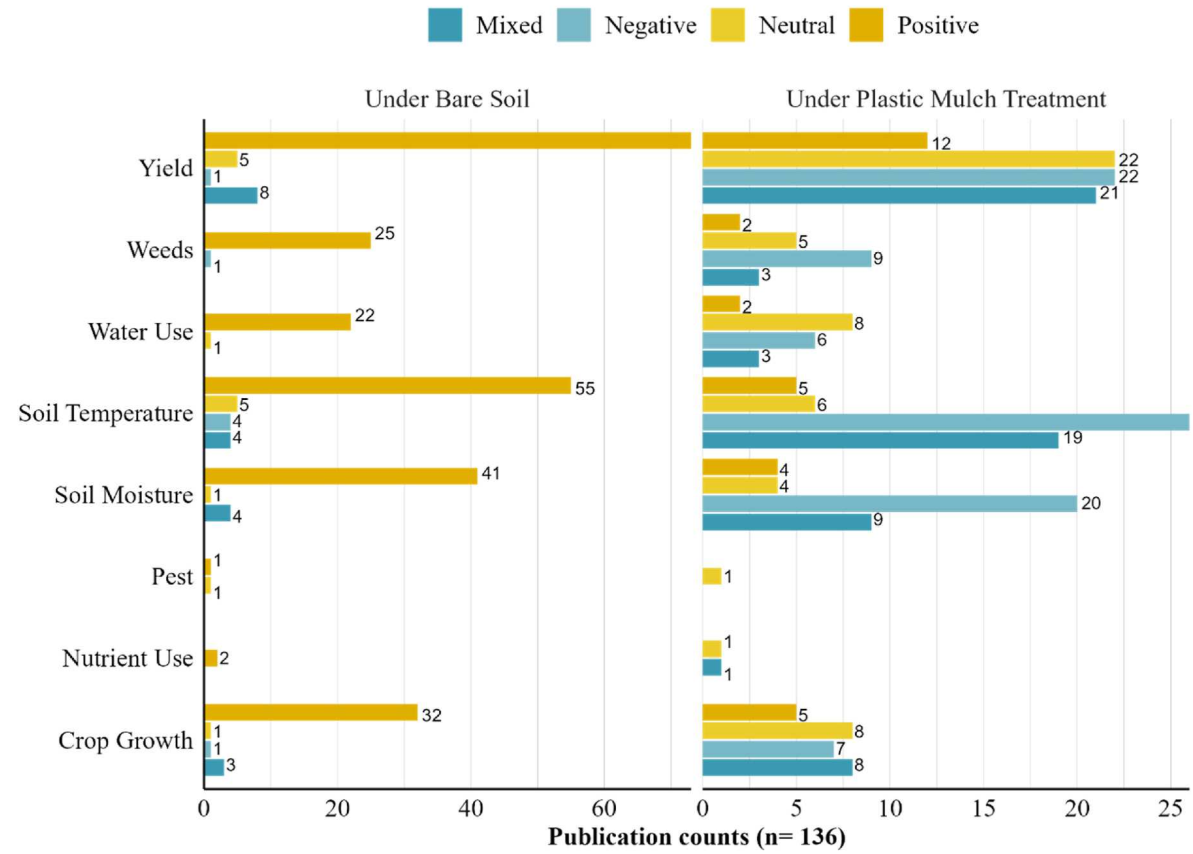

Fig. 9. Effects of biodegradable mulch application on studied agronomic factors compared to bare soil and plastic mulch treatment. **Note:** *Effects on crop yields [Yield], Effects on pest and diseases [Pest], Effects on soil moisture [Soil Moisture], Effects on soil temperature [Soil Temperature], Effects on weeds control [Weeds], Effects on water use efficiency [Water Use], Effects on soil nutrients use efficiency [Nutrient Use].*

Graminoid, Tree Orchard, and Pasture groups having yield increases compared to no-mulching or plastic mulch in 80.0%, 61.0%, 57.1%, and 60.0% of instances, respectively (SI Fig. 10).

3.5. Factors affecting the suitability and effectiveness of biodegradable mulches

The ability of biodegradable mulches to sustain their performance and mechanical properties throughout the growing season remain crucial for their suitability in agricultural applications, especially in efforts to replace plastic mulches. Biodegradable mulches are designed to be suitable for agriculture application with minimum possible thickness aimed at reducing cost and ensuring optimal biodegradation rate while retaining satisfactory mechanical performance throughout the growing season [110]. Field trials have demonstrated that depending on the thickness of the mulch, degradation can begin between two and three months [111]. Under irrigated agricultural soil conditions, the mulch is shown to readily degrade over 90% within four to six months in such management systems.

One of the main factors that shape the suitability of biodegradable mulch applications is the local climate conditions. Thus, over 63.7% of the studies monitored atmospheric temperature during experiments highlighting the importance of this environmental factor on agronomic factors and degradation rates (Fig. 10). For instance, Samuelson et al. [28] observed a relatively greater degradation rate at Lincoln, Nebraska USA due in part to higher mean annual temperatures (10.6 °C) compared to 8.8 °C in Scottsbluff, Nebraska USA. Similarly, Li et al. [112] found a higher deterioration rate (98%) in a study site with warmer temperatures at Lubbock in Texas, United States compared to a 11% degradation rate at Mount Vernon, Washington State USA.

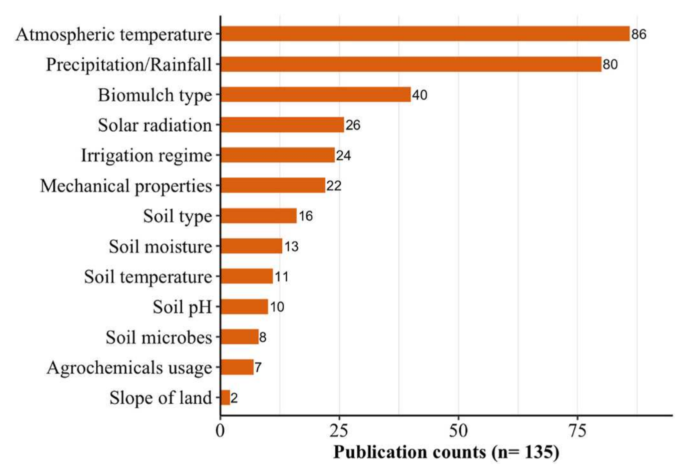

Fig. 10. Monitored environmental conditions during primary study experiments.

Considering that microbial activity tends to double with every 10 °C increase in temperature, a phenomenon often denoted as the Q_{10}, it is conceivable that there is a temperature threshold for the biodegradation of these mulches [76]. About 59.3% of the studies found the suitability of the mulches to be shaped by precipitation. In a field trial, Feng et al. [78] observed a relatively higher degradation rate in 2017 under conditions with higher precipitation compared to other experimental years. Evidence showed that total monthly precipitation of 127.5–134.0 mm resulted in a rapid loss of the mulch functionality [113]. These studies suggest that the combined effect of higher temperature and precipitation may result in rapid mineralization of the mulch.

The intensity of solar radiance (UV) reaching the mulch surface determines biodegradable mulch capacity to maintain its mechanical performance over the growing season. Experimental results showed UV [photodegradation] as one of the main degradation mechanisms on field application [111]. For example, Briassoulis [110] found a high dose of UV radiation (above 28 MJm^{-2} per day) to have detrimental effects on the elongation at break of the mulches. Soil attributes such as the level of temperature, moisture, pH, microbes' diversity, and texture class were also found to be relevant to biodegradable mulch suitability on the field (Fig. 10). For example, Samuelson et al. [28] and Li et al. [76] investigated the effects of soil temperature and moisture on degradation rate of biodegradable mulches, during deployment, in contrasting sites and found rapid mulch disintegration in sites with higher soil temperatures and moisture content. Soil microbes, including bacteria and fungi, accelerate the decomposition process during deployment by actively feeding on the mulch as well as produce enzymes that break down complex organic materials in biodegradable mulches [15,64,114]. Soil pH level between 6.2 and 7.5 provides an optimum condition for most of the microbes involved in biodegradation in the soil [115]. Finer soil texture class (silt and loamy soils) are also found to be more suitable for biodegradable mulch application (Samuelson et al. [28].

The types and mechanical properties of biodegradable mulches affect their suitability and effectiveness on the desired agronomic factors (Table 5). Different mulch colors including red, blue, infrared thermal green, brown, silver, black, and white are currently being experimented toward achieving various agronomic purposes. White transparent mulches result in increased soil temperature and early crop maturity because of the ability to solarize the soils, and further serving as an environmentally friendly method of physical disinfection [116]. Komariah et al. [117] observed a higher soil temperature (26.69 °C) under transparent mulch compared to black plastic mulch (26.07 °C). However, there were varied reported impacts of the color of mulches on soil temperature. For example, Jahan et al. [118] and Jia et al. [119] reported that black and blue plastics increase soil temperature while clear and white plastics decrease it. Moreover, mulch color affects the photosynthetically active radiation (PAR) reaching the soil under mulch. The effectiveness of mulches in controlling weeds was reported to depend on their ability to moderate the amount of PAR reaching the mulched soil [62,99]. Biodegradable mulches with a PAR total transmissivity coefficient from 0.2 to 4.1 have been found to have a greater ability to reduce weed growth [83]. Different color pigments can also act as UV-shielding agents to prevent or delay photo-degradation [116].

Overall the primary studies suggest that color type significantly influences mulch effects on soil temperature, moisture and water holding capacity (Table 5). Moreover, higher crop yields are reported in the use of colored plastic mulches [83,120,121]. For instance, Zong et al. [98] observed higher corn yields under black biodegradable mulch compared to transparent plastic mulch. The thickness of biodegradable mulches also influences their ability to meet various usage needs (Table 5). Thus, thicker mulch has the ability to reduce soil water evaporation and is more effective in soil water retention. Biodegradable mulches with a thickness of about 8–12 μm have proven the potential of meeting mechanical performance requirements and effectively maintaining soil temperature and moisture at levels completely consistent with plastic mulch ([88]; Z [82]). Moreover, Fontenot et al. [122] observed that 13 mm thicker biodegradable mulch performed (8.7 fruit, 2.4 Kg) comparably to 1.0 mm thick plastic mulch (5.8 fruit, 1.9 Kg) in terms of both average harvested number of fruits and weights.

Moreover, field-scale management practices such as irrigation regimes, timing of mulch application, and agrochemical usages were found to influence the effects of biodegradable mulches in agriculture application. Thus, Khan et al. [86] showed that biodegradable mulches blended with herbicide can effectively inhibit the growth of broadleaf weed species and may be of potential importance in a wide variety of horticultural and agricultural applications. Crop canopy cover was found to mediate mulch effects on soil temperature [88]. Alamro et al. [123] noted that crop/vegetation canopy cover reduced solar radiation reaching the surface of soil under mulch, which minimized soil water evaporation [123]. Irrigation practices such as ridge-furrow rainwater harvesting together with biodegradable mulching increased soil temperature and moisture content at ridge tops as well as increasing fodder yield by 7–18% compared to flat planting [93]. The level of mulch effectiveness on the agronomic factors was also found to be dependent on timing of application and the stage of crop growth [119,124,125]. The influence of mulching on lettuce biomass was dependent on the timing of sowing [105]. Ao et al. [124] indicated that there were less significant differences in soil temperature between biodegradable mulch and plastic mulch when crops reached their jointing stage.

Lastly, in terms of adoption, the ease of application, end-of-life management, organic regulations, effects on productivity, awareness and information availability, and the economics of use were the major determinants of farmers' decisions to use biodegradable mulch. The current prices of biodegradable mulches are higher than plastic mulch, which hampers their adoption in the field [126]. A survey of farmers found the cost and labor savings associated with transitioning from plastic mulch to biodegradable mulch were the primary factors that influenced the economic feasibility of biodegradable mulch adoption [19,31]. Moreover, while biodegradable mulch is more expensive than plastic, some farmers are motivated by end-of-life management cost savings and its environmental benefits [35,127,128]. Biodegradable mulches do not require waste removal after the growing season as they can be tilled into the soil, where they degrade into water, carbon dioxide, and microbial biomass [129]. The other major adoption barriers noted in the primary studies were insufficient biodegradable mulch information and knowledge among farmers [27,130]. Also, the USA National Organic Program requirements for biodegradable mulch to meet certain criteria, such as being made from biobased materials and 90% degradable in a specified timeframe, affect adoption rates due to the availability and cost of products that meet these standards [27,35].

4. Discussion and conclusions

Our systematic review of studies evaluating the use of synthesized biodegradable mulch films for agricultural applications illustrates a significant increase in interest in these materials across major agricultural production regions since the 1990s. The agronomic factors studied in each region vary, with a significant emphasis on crop yields in developed regions known for industrial agriculture, such as Eastern Asia, North America, and parts of Europe. Overall, we find that majority of studies reported positive effects of biodegradable mulch use on all agronomic factors when compared to a no-mulch control group. Similar to Liu et al. [10] and Tofanelli and Wortman [39], we find that, in comparison to conventional plastic mulch, most studies report that biodegradable mulch offers similar or reduced levels of agronomic improvements. However, soil temperature and soil moisture benefits, in particular, are notably reduced for biodegradable mulch films relative to plastic mulch. In addition, our findings point to differences in biodegradable mulch effects across agronomic impact studied, biomes, crop types, and mulch types. Thus, while biodegradable films have shown positive agronomic effects compared to no mulch [131], their ability to provide benefits comparable to plastic mulch films are influenced by contextual factors. Specifically, contextual factors such as climate, crop type, and soil properties differentially influence the effectiveness of different biodegradable mulch products in controlling weeds, conserving moisture, and improving soil temperature and yields.

There was no noticeable disproportionate reporting of positive effects of biodegradable mulch use from specific countries' sub-regional groups other than for regions located in hot climates, where very few negative effects were reported. Studies conducted in global biomes with hot summers, arid, and/or humid climate conditions often correlate with more positive agronomic impacts, suggesting a higher suitability of biodegradable mulch in these conditions. However, additional field experiments with biodegradable mulch in these biomes are warranted given the relatively small number of studies conducted in these areas. We also find that Mater-Bi and paper mulches exhibited a greater degree of effectiveness for certain agronomic factors, with paper mulches excelling in weed control and Mater-Bi in enhancing yields. Relatedly, a greater proportion of positive impacts of biodegradable mulch use relative to conventional plastic film were observed specifically for bush fruits and graminoid crops which were most frequently studied in Italy and China, respectively.

Although this review suggests that biodegradable mulch almost always provides agronomic benefits relative to not mulching and can often provide comparable benefits as conventional plastic mulch, particularly for more arid environments, the realities of interactions between environmental conditions, mulch characteristics, and crop type strongly influence the agronomic and economic benefits of biodegradable mulch use. While the details of farm practice and management are never trivial for any adopted innovation or technology, these details may be of pronounced importance relative to alternatives such as plastic mulch films due to the importance of biodegradable mulch degradation rates on agronomic impacts and the importance of environmental conditions on degradation rates.

While there are numerous studies that have conducted experiments using biodegradable mulch films for crop production, our review points to a few areas for future consideration. In particular, for sprayable mulch films, details on the mulch application process and resulting film characteristics are often insufficient to replicate the experiment or determine if observed variations in impacts are the result of varying film thickness or consistency of coverage or mulch formulation. In many experiments, regardless of mulch type, information on dates of application, dates and method of planting, climate conditions, and observations of degradation in the field are incomplete, leading to uncertainty about the source of variations in observed impacts across experiments. Future research would benefit from more detailed collection and reporting of information on mulch application processes and mulch characteristics at the time of application and throughout the growing season. In addition, as degradation rates are of prime importance for biodegradable mulch films and are impacted by factors that also influence agronomic factors such as yield, studies that incorporate plot or field-scale collection of environmental conditions such as air temperature, precipitation, and UV radiance may be useful for uncovering thresholds of biophysical suitability of biodegradable mulch film use.

Our finding that more positive effects of biodegradable mulch use are found in hotter and more arid climates, as well as findings that suggest non-random testing of specific mulch products, with specific crops, in specific areas of the world, lead us to urge caution in interpretation and extrapolation of field experiment results to other contexts. Future research would benefit from not just additional environmental monitoring but also from more studies conducted using experimental designs that intentionally and systematically vary crop, mulch product, and climate conditions.

We also note a lack of field studies examining the role of microorganisms in biodegradable mulch film degradation and agronomic benefits both during the growing season and after being tilled-in, as well as limited studies examining the impact of biodegradable mulch film use on microbial ecology of agricultural fields [40]. Given that "biodegradable" suggests that degradation occurs through biological metabolic processes, the interactions between microorganisms and biodegradable mulch films as they are used in agricultural practice and the potential for long-term soil health improvements in the field should be a fruitful area of future investigation. Impacts of biodegradable mulch films on weed and pest control were also relatively understudied in comparison to studies that investigated factors such as yield, soil moisture, and soil temperature. Lastly, there was a lack of studies examining the potential of biodegradable mulch films to support environmental benefits such as reductions in carbon emissions and other water and air pollutants in field applications.

This study provides an overview of the current state of biodegradable mulch studies in agricultural settings and summarizes what the state of knowledge is regarding the potential for biodegradable mulch films to offer benefits for crop production, soil health, and farmer economics across varied environmental and experimental contexts. However, our review is limited by the search terms and exclusion criteria employed. Studies that examined biodegradation rates of biodegradable mulch films in laboratory settings, for example, were excluded from this review but may offer insight into the impact of climate conditions on degradation rates. Furthermore, while our review captures information on the direction of biodegradable mulch use impacts on agronomic factors relative to controls and alternative treatments the magnitude of these effects for each treatment trial were not collected. While our results suggest improvements over no mulch controls and comparability with conventional plastic mulch across many contexts, information on the exact magnitude of these differences and the extent of variability across trials are highly relevant to agricultural practice and decision-making.

CRediT authorship contribution statement

Michael Madin: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Katherine Nelson:** Writing – original draft, Supervision, Data curation, Conceptualization. **Kanij Fatema:** Writing – review & editing, Data curation. **Karina Schoengold:** Writing – review & editing, Data curation, Conceptualization. **Abhilekha Dalal:** Writing – review & editing, Data curation. **Ikenna Onyekwelu:** Writing – review & editing, Data curation. **Rushrukh Rayan:** Writing – review & editing, Data curation. **Sanaz Saki Norouzi:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2024.101095.

References

[1] A. Mirzabaev, A. Strokov, P. Krasilnikov, The impact of land degradation on agricultural profits and implications for poverty reduction in Central Asia, Land Use Pol. 126 (2023) 106530, https://doi.org/10.1016/j.landusepol.2022.106530.
[2] F. Batibeniz, M. Ashfaq, N.S. Diffenbaugh, K. Key, K.J. Evans, U.U. Turuncoglu, B. Önol, Doubling of U.S. Population exposure to climate extremes by 2050, Earth's Future 8 (4) (2020), https://doi.org/10.1029/2019EF001421.
[3] B.I. Cook, T.R. Ault, J.E. Smerdon, Unprecedented 21st century drought risk in the American southwest and central plains, Sci. Adv. 1 (1) (2015), https://doi.org/10.1126/SCIADV.1400082.
[4] IPBES, in: L. Montanarella, R. Scholes, A. Brainich (Eds.), The IPBES Assessment Report on Land Degradation and Restoration, 2018.
[5] V. Piñeiro, J. Arias, J. Dürr, P. Elverdin, A.M. Ibáñez, A. Kinengyere, C.M. Opazo, N. Owoo, J.R. Page, S.D. Prager, M. Torero, A scoping review on incentives for

adoption of sustainable agricultural practices and their outcomes, Nat. Sustain. 3 (10) (2020) 809–820, https://doi.org/10.1038/s41893-020-00617-y.
[6] P. Smith, K. Calvin, J. Nkem, D. Campbell, F. Cherubini, G. Grassi, V. Korotkov, A. Le Hoang, S. Lwasa, P. McElwee, E. Nkonya, N. Saigusa, J.F. Soussana, M. A. Taboada, F.C. Manning, D. Nampanzira, C. Arias-Navarro, M. Vizzarri, J. House, A. Arneth, Which practices co-deliver food security, climate change mitigation and adaptation, and combat land degradation and desertification? Global Change Biol. 26 (3) (2020) 1532–1575, https://doi.org/10.1111/GCB.14878.
[7] FAO, Sustainable Development and Natural Resources Management. *Twenty- Fifth Conference, Paper C 89/2 -*, Supplement 2 (1989) 1–53. https://www.fao.org/3/z4961en/z4961en.pdf.
[8] M. Kassie, M. Jaleta, B. Shiferaw, F. Mmbando, M. Mekuria, Adoption of interrelated sustainable agricultural practices in smallholder systems: evidence from rural Tanzania, Technol. Forecast. Soc. Change 80 (3) (2013) 525–540, https://doi.org/10.1016/J.TECHFORE.2012.08.007.
[9] H. Eswaran, R. Lal, P.F. Reich, Land Degradation: an Overview. *Response To Land Degradation*, vols. 20–35, 2019, https://doi.org/10.1201/9780429187957-4.
[10] E. Liu, L. Zhang, W. Dong, C. Yan, Biodegradable plastic mulch films in agriculture: feasibility and challenges, Environ. Res. Lett. (2021), https://doi.org/10.1088/1748-9326/abd211.
[11] X. Ni, W. Song, H. Zhang, X. Yang, L. Wang, Effects of mulching on soil properties and growth of tea olive (osmanthus fragrans), PLoS One 11 (8) (2016) e0158228, https://doi.org/10.1371/JOURNAL.PONE.0158228.
[12] E. Schettini, G.M. Vox Dipartimento di Progettazione Gestione Malinconico, B. Immirzi, Physical properties of innovative biodegradable spray coating for soil mulching in greenhouse cultivation, Acta Hortic. 14 (691) (2004).
[13] M.B. Samuelson, E.V. Reid, R. Drijber, E. Jeske, H. Blanco-Canqui, M. Mamo, I. Kadoma, S.E. Wortman, Effects of compost, cover crops, and local conditions on degradation of two agricultural mulches in soil, Renew. Agric. Food Syst. 37 (2) (2022) 128–141, https://doi.org/10.1017/S1742170521000405.
[14] G. Vox, G. Santagata, M. Malinconico, B. Immirzi, G.S. Mugnozza, E. Schettini, Biodegradable films and spray coatings as eco-friendly alternative to petro-chemical derived mulching films, J. Agric. Eng. 44 (2s) (2013), https://doi.org/10.4081/jae.2013.286.
[15] X. Shan, W. Zhang, Z. Dai, J. Li, W. Mao, F. Yu, J. Ma, S. Wang, X. Zeng, Comparative analysis of the effects of plastic mulch films on soil nutrient, yields and soil microbiome in three vegetable fields, Agronomy 12 (2) (2022) 506, https://doi.org/10.3390/AGRONOMY12020506.
[16] Y. Wu, F. Huang, Z. Jia, X. Ren, T. Cai, Response of soil water, temperature, and maize (Zea may L.) production to different plastic film mulching patterns in semi-arid areas of northwest China, Soil and Tillage Research 166 (2017) 113–121, https://doi.org/10.1016/j.still.2016.10.012.
[17] Z. Steinmetz, C. Wollmann, M. Schaefer, C. Buchmann, J. David, J. Tröger, K. Muñoz, O. Frör, G.E. Schaumann, Plastic mulching in agriculture. Trading short-term agronomic benefits for long-term soil degradation? Science of the Total Environment 550 (2016) 690–705.
[18] M.A.M. Akhir, M. Mustapha, Formulation of biodegradable plastic mulch film for agriculture crop protection: a review, Polym. Rev. 1–29 (2022).
[19] M. Velandia, R. Rejesus, C. Clark, K.L. DeLong, A. Wszelaki, S. Schexnayder, K. Jensen, Evaluating the relationship between fruit and vegetable growers use of plastic biodegradable mulches, and environmental stewardship and labor savings: the case of Tennessee fruit and vegetable farmers, Sustainability 12 (5) (2020) 2075, https://doi.org/10.3390/su12052075.
[20] M. Velandia, A. Smith, A. Wszelaki, T. Marsh, The Economics of Adopting Biodegradable Plastic Mulch Films, 2019. https://ag.tennessee.edu/biodegradablemulch/Pages/biomulchprojects.aspx.
[21] B. Madrid, S. Wortman, D.G. Hayes, J.M. DeBruyn, C. Miles, M. Flury, T.L. Marsh, S.P. Galinato, K. Englund, S. Agehara, L.W. DeVetter, End-of-Life management options for agricultural mulch films in the United States—a review, Front. Sustain. Food Syst. 6 (2022) 921496, https://doi.org/10.3389/FSUFS.2022.921496/BIBTEX.
[22] M. Velandia, S. Galinato, A. Wszelaki, Economic evaluation of biodegradable plastic films in Tennessee pumpkin production, Agronomy 10 (1) (2019) 51, https://doi.org/10.3390/agronomy10010051.
[23] H. Gao, C. Yan, Q. Liu, W. Ding, B. Chen, Z. Li, Effects of plastic mulching and plastic residue on agricultural production: a meta-analysis, Sci. Total Environ. 651 (2019) 484–492.
[24] K. Koskei, A.N. Munyasya, Y.B. Wang, Z.Y. Zhao, R. Zhou, S.N. Indoshi, W. Wang, W.K. Cheruiyot, D.M. Mburu, A.B. Nyende, Y.C. Xiong, Effects of increased plastic film residues on soil properties and crop productivity in agro-ecosystem, J. Hazard Mater. 414 (2021), https://doi.org/10.1016/j.jhazmat.2021.125521.
[25] F. Shah, W. Wu, Use of plastic mulch in agriculture and strategies to mitigate the associated environmental concerns, in: Advances in Agronomy, vol. 164, Academic Press Inc, 2020, pp. 231–287, https://doi.org/10.1016/bs.agron.2020.06.005.
[26] Transparency Market Research. *Agricultural Films Market for Greenhouse, Mulching and Silage Applications - Global Industry Analysis, Size, Share, Growth, Trends and Forecast*, 2013, pp. 2013–2019. https://www.transparencymarketresearch.com/agricultural-film.html.
[27] J.R. Goldberger, R.E. Jones, C.A. Miles, R.W. Wallace, D.A. Inglis, Barriers and bridges to the adoption of biodegradable plastic mulches for US specialty crop production, Renew. Agric. Food Syst. 30 (2) (2015) 143–153, https://doi.org/10.1017/S1742170513000276.
[28] Samuelson, M. B., Reid, E. V, Drijber, R., Jeske, E., Blanco-Canqui, H., Mamo, M., Kadoma, I., & Wortman, S. E. (2022). Effects of compost, cover crops, and local conditions on degradation of two agricultural mulches in soil. *Renewable Agriculture and Food Systems*, *37*(2), 128–141. https://doi.org/10.1017/S1742170521000405.
[29] J. Goldberger, C. Lyons, Use of plastic mulch films in U.S. Strawberry production. Results from a multi-state survey about U.S. Strawberry growers' perceptions and experiences of plastic mulch films. https://ag.tennessee.edu/biodegradablemulch/Documents/Strawberry_Grower_Survey_Summary_Report-February2017.pdf, 2017.
[30] D. Briassoulis, Analysis of the mechanical and degradation performances of optimised agricultural biodegradable films. *POLYMER DEGRADATION AND*, STABILITY 92 (6) (2007) 1115–1132. https://doi.org/10.1016/j.polymdegradstab.2007.01.024.
[31] T. Sun, G. Li, T.Y. Ning, Z.M. Zhang, Q.H. Mi, R. Lal, Suitability of mulching with biodegradable film to moderate soil temperature and moisture and to increase photosynthesis and yield in peanut, Agric. Water Manag. 208 (March 2017) (2018) 214–223, https://doi.org/10.1016/j.agwat.2018.06.027.
[32] W.K. Cheruiyot, W. Wang, S.G. Zhu, L. Kavagi, X.C. Zhang, D.M. Mburu, M.S. Ma, A.N. Munyasya, K. Koskei, S.N. Indoshi, A.B. Nyende, Environmental and economic impacts of biodegradable plastic film mulching on rainfed maize: evaluations on sustainability and productivity, ACS Agric. Sci. & Technol. 2 (5) (2022 Oct 4) 908–918.
[33] Prokopy, L. S., Floress, K., Arbuckle, J. G., Church, S. P., Eanes, F. R., Gao, Y., Gramig, B. M., Ranjan, P., & Singh, A. S. (2019). Adoption of agricultural conservation practices in the United States: Evidence from 35 years of quantitative literature. *Journal of Soil and Water Conservation*, *74*(5), 520–534. https://doi.org/10.2489/jswc.74.5.520Prokopy et al., 2019.
[34] J. Lu, P. Ranjan, K. Floress, J.G. Arbuckle, S.P. Church, F.R. Eanes, Y. Gao, B. M. Gramig, A.S. Singh, L.S. Prokopy, A meta-analysis of agricultural conservation intentions, behaviors, and practices: Insights from 35 years of quantitative literature in the United States, Journal of Environmental Management 323 (2022) 116240. https://doi.org/10.1016/J.JENVMAN.2022.116240.
[35] K.E. Dentzman, J.R. Goldberger, Organic standards, farmers' perceptions, and the contested case of biodegradable plastic mulch in the United States, J. Rural Stud. 73 (2020) 203–213, https://doi.org/10.1016/j.jrurstud.2019.11.002.
[36] C. Miles, L. DeVetter, S. Ghimire, D.G. Hayes, Suitability of biodegradable plastic mulches for organic and sustainable agricultural production systems, Hortscience 52 (1) (2017) 10–15.
[37] M. Sander, Biodegradation of polymeric mulch films in agricultural soils: concepts, knowledge gaps, and future research directions, Environ. Sci. Technol. 53 (5) (2019) 2304–2315.
[38] M. Menossi, M. Cisneros, V.A. Alvarez, C. Casalongué, Current and emerging biodegradable mulch films based on polysaccharide bio-composites. A review, Agron. Sustain. Dev. 41 (4) (2021) 53.
[39] M.B. Tofanelli, S.E. Wortman, Benchmarking the agronomic performance of biodegradable mulches against polyethylene mulch film: a meta-analysis, Agronomy 10 (10) (2020) 1618.
[40] M. Zhang, Y. Xue, T. Jin, K. Zhang, Z. Li, C. Sun, Q. Mi, Q. Li, Effect of long-term biodegradable film mulch on soil physicochemical and microbial properties, Toxics 10 (3) (2022) 129, https://doi.org/10.3390/toxics10030129.
[41] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement, BMJ 339 (7716) (2009) 332–336. https://doi.org/10.1136/BMJ.B2535.
[42] E.M. Grames, A.N. Stillman, M.W. Tingley, C.S. Elphick, An automated approach to identifying search terms for systematic reviews using keyword co-occurrence networks, Methods Ecol. Evol. 10 (10) (2019) 1645–1654, https://doi.org/10.1111/2041-210X.13268.
[43] M.J. Westgate, revtools: an R package to support article screening for evidence synthesis, Res. Synth. Methods 10 (4) (2019) 606–614, https://doi.org/10.1002/jrsm.1374.
[44] V. Acosta-Martínez, R. Lascano, F. Calderón, J.D. Booker, T.M. Zobeck, D. R. Upchurch, Dryland cropping systems influence the microbial biomass and enzyme activities in a semiarid sandy soil, Biol. Fertil. Soils 47 (6) (2011) 655–667, https://doi.org/10.1007/s00374-011-0565-1.
[45] N. Alpert, Recent developments in petroleum products for agriculture, in: 6th World Petroleum Congress, 1963.
[46] Y. Fu, J.H. Xie, L.H. Zhang, M.H. Zhang, S.L. Hou, Study on the residue of plastic film in inner Mongolia autonomous region, Appl. Mech. Mater. 448–453 (2014) 674–679, https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMM.448-453.674.
[47] D. Gilead, A controllable, photodegradable polyethylene film for agriculture, Int. J. Polymeric Mater. Polymeric Biomater. 6 (3–4) (1978) 185–196, https://doi.org/10.1080/00914037808077908.
[48] J. Huang, A.S. Shetty, M. Wang, Biodegradable plastics: a review, Adv. Polym. Technol. 10 (1) (1990) 23–30.
[49] W. Qin, C. Hu, O. Oenema, Soil mulching significantly enhances yields and water and nitrogen use efficiencies of maize and wheat: a meta-analysis, Sci. Rep. 5 (2015) 16210.
[50] T. Bozada, J. Borden, J. Workman, M. Del Cid, J. Malinowski, T. Luechtefeld, Sysrev: a fair platform for data curation and systematic evidence review, Front. Artif. Intelli. 4 (2021), https://doi.org/10.3389/frai.2021.685298.
[51] A.M.C. Verdú, M.T. Mas, R. Josa, M. Ginovart, The effect of a prototype hydromulch on soil water evaporation under controlled laboratory conditions, J. Hydrol. Hydromechanics 68 (4) (2020) 404–410, https://doi.org/10.2478/JOHH-2020-0018.
[52] G. Okyay, S. Karagöz, A. Ulaş, İ. Özen, Efficiency of an agrotextile surface structure possessing fertilizer and water management coupled with mulching

property in romaine lettuce growth trials, J. Text. Inst. 111 (12) (2020) 1735–1744, https://doi.org/10.1080/00405000.2020.1727268.
[53] M.W.R. Marral, M.B. Khan, F. Ahmad, S. Farooq, M. Hussain, The influence of transgenic (Bt) and non-transgenic (non-Bt) cotton mulches on weed dynamics, soil properties and productivity of different winter crops, PLoS One 15 (9) (2020) e0238716, https://doi.org/10.1371/journal.pone.0238716.
[54] A. Cirujeda, A. Anzalone, J. Aibar, M.M. Moreno, C. Zaragoza, Purple nutsedge (Cyperus rotundus L.) control with paper mulch in processing tomato, Crop Protect. 39 (2012) 66–71, https://doi.org/10.1016/j.cropro.2012.03.028.
[55] E. Rudnik, D. Briassoulis, Comparative biodegradation in soil behaviour of two biodegradable polymers based on renewable Resources, J. Polym. Environ. 19 (1) (2011) 18–39, https://doi.org/10.1007/S10924-010-0243-7/TABLES/8.
[56] E. Dinerstein, D. Olson, A. Joshi, C. Vynne, N.D. Burgess, E. Wikramanayake, N. Hahn, S. Palminteri, P. Hedao, R. Noss, M. Hansen, H. Locke, E.C. Ellis, B. Jones, C.V. Barber, R. Hayes, C. Kormos, V. Martin, E. Crist, M. Saleem, An ecoregion-based approach to protecting half the terrestrial realm, Bioscience 67 (6) (2017) 534–545, https://doi.org/10.1093/biosci/bix014.
[57] UN Statistics Division, *UNSD — Methodology. Standard country or area codes for statistical use (M49)*. https://unstats.un.org/unsd/methodology/m49.
[58] NRCS. USDA, *USDA NRCS National Plants Database*. https://plants.usda.gov/home/plantProfile?symbol=ORYZA.
[59] M.B. Anunciado, L.C. Wadsworth, S. Ghimire, C. Miles, J.C. Moore, A.L. Wszelaki, D.G. Hayes, Deterioration of soil-biodegradable mulch films during storage and its impact on specialty crop production, HortTechnology 31 (6) (2021) 798–809, https://doi.org/10.21273/HORTTECH04922-21.
[60] R.L. Shogren, R.C. Hochmuth, Field evaluation of watermelon grown on paper-polymerized vegetable oil mulches, Hortscience 39 (7) (2004) 1588–1591, https://doi.org/10.21273/HORTSCI.39.7.1588.
[61] M.V. Braunack, R. Adhikari, G. Freischmidt, P. Johnston, P.S. Casey, Y. Wang, K. L. Bristow, L. Filipović, V. Filipović, Initial experimental experience with a sprayable biodegradable polymer membrane (SBPM) technology in cotton, Agronomy 10 (4) (2020), https://doi.org/10.3390/agronomy10040584.
[62] A. Anzalone, A. Cirujeda, J. Aibar, G. Pardo, C. Zaragoza, Effect of biodegradable mulch materials on weed control in processing tomatoes, Weed Technol. 24 (3) (2010) 369–377, https://doi.org/10.1614/wt-09-020.1.
[63] A. Sekara, R. Pokluda, E. Cozzolino, L. del Piano, A. Cliciniello, G. Caruso, Plant growth, yield, and fruit quality of tomato affected by biodegradable and non-degradable mulches, Hortic. Sci. (HORTSCI) 46 (3) (2019) 138–145, https://doi.org/10.17221/218/2017-HORTSCI.
[64] S. Bandopadhyay, H.Y. Sintim, J.M. DeBruyn, Effects of biodegradable plastic film mulching on soil microbial communities in two agroecosystems, PeerJ 8 (2020) e9015, https://doi.org/10.7717/peerj.9015.
[65] D.G. Hayes, L.C. Wadsworth, H.Y. Sintim, M. Flury, M. English, S. Schaeffer, A. M. Saxton, Effect of diverse weathering conditions on the physicochemical properties of biodegradable plastic mulches, Polym. Test. 62 (2017) 454–467, https://doi.org/10.1016/j.polymertesting.2017.07.027.
[66] H.Y. Sintim, A.I. Bary, D.G. Hayes, L.C. Wadsworth, M.B. Anunciado, M. E. English, S. Bandopadhyay, S.M. Schaeffer, J.M. DeBruyn, C.A. Miles, J. P. Reganold, M. Flury, In situ degradation of biodegradable plastic mulch films in compost and agricultural soils, Sci. Total Environ. 727 (2020) 138668, https://doi.org/10.1016/j.scitotenv.2020.138668.
[67] X. Ren, P. Zhang, X. Chen, J. Guo, Z. Jia, Effect of different mulches under rainfall concentration system on corn production in the semi-arid areas of the loess plateau, Sci. Rep. 6 (1) (2016) 19019, https://doi.org/10.1038/srep19019.
[68] R.M. Qiao, C.P. Zhao, J.L. Liu, M.L. Zhang, W.Q. He, Synthesis of novel ultraviolet absorbers and preparation and field application of anti-ultraviolet aging PBAT/UVA films, Polymers 14 (7) (2022) 1434, https://doi.org/10.3390/POLYM14071434.
[69] D. Briassoulis, F. Degli Innocenti, *Standards For Soil Biodegradable Plastics*. 139–168, 2017, https://doi.org/10.1007/978-3-662-54130-2_6.
[70] D. Kopitar, P. Marasovic, N. Jugov, I. Schwarz, Biodegradable nonwoven agrotextile and films—a review, Polymers 14 (11) (2022), https://doi.org/10.3390/POLYM14112272.
[71] Hayes, D. G., & Flury, M. (2018). *Summary and Assessment of EN 17033:2018, a New Standard for Biodegradable Plastic Mulch Films*. Hayes & Flury, 2018.
[72] S. Fontanazza, A. Restuccia, G. Mauromicale, A. Scavo, C. Abbate, Pseudomonas putida isolation and quantification by real-time PCR in agricultural soil biodegradable mulching, Agriculture 11 (8) (2021) 782, https://doi.org/10.3390/agriculture11080782.
[73] K. Mosnáčková, M. Šlosár, J. Kollár, I. Janigová, A. Šišková, Š. Chmela, W. Sikorska, D. Perďochová, I. Gálisová, P. Alexy, I. Chodák, J. Mosnáček, Ageing of plasticized poly(lactic acid)/poly(3-hydroxybutyrate)/carbon black mulching films during one season of sweet pepper production, Eur. Polym. J. 114 (2019) 81–89, https://doi.org/10.1016/j.eurpolymj.2019.02.010.
[74] H.Y. Sintim, S. Bandopadhyay, M.E. English, A.I. Bary, J.M. DeBruyn, S. M. Schaeffer, C.A. Miles, J.P. Reganold, M. Flury, Impacts of biodegradable plastic mulches on soil health, Agric. Ecosyst. Environ. 273 (2019) 36–49, https://doi.org/10.1016/j.agee.2018.12.002.
[75] D. Briassoulis, Mechanical behaviour of biodegradable agricultural films under real field conditions, Polym. Degrad. Stabil. 91 (6) (2006) 1256–1272, https://doi.org/10.1016/j.polymdegradstab.2005.09.016.
[76] C. Li, J. Moore-Kucera, C. Miles, K. Leonas, J. Lee, A. Corbin, D. Inglis, Degradation of potentially biodegradable plastic mulch films at three diverse U.S. Locations, Agroecol. Sustain. Food Syst. 38 (8) (2014) 861–889, https://doi.org/10.1080/21683565.2014.884515.
[77] Ghimire, S. (2018). *Biodegradable mulch for pumpkin and sweet corn production: crop yield and quality, and mulch degradation* (Issue May)Ghimire, 2018.
[78] Y. Feng, H. Shi, X. Cao, Q. Miao, Q. Jia, J. Li, N. Wang, K. Zhu, Numerical modeling of soil water-heat transport under oxo-biodegradable film mulch and the optimal mulching period, J. Irrigat. Drain. Eng. 147 (9) (2021), https://doi.org/10.1061/(ASCE)IR.1943-4774.0001555.
[79] T. Kijchavengkul, R. Auras, M. Rubino, E. Alvarado, J.R. Camacho Montero, J. M. Rosales, Atmospheric and soil degradation of aliphatic-aromatic polyester films, Polym. Degrad. Stabil. 95 (2) (2010) 99–107, https://doi.org/10.1016/j.polymdegradstab.2009.11.048.
[80] E. Chiellini, P. Cinelli, F. Chiellini, S.H. Imam, Environmentally degradable bio-based polymeric blends and composites, Macromol. Biosci. 4 (3) (2004) 218–231, https://doi.org/10.1002/mabi.200300126.
[81] L. Sartore, G. Vox, E. Schettini, Preparation and performance of novel biodegradable polymeric materials based on hydrolyzed proteins for agricultural application, J. Polym. Environ. 21 (3) (2013) 718–725, https://doi.org/10.1007/s10924-013-0574-2.
[82] Z. Wang, Q. Wu, B. Fan, X. Zheng, J. Zhang, W. Li, L. Guo, Effects of mulching biodegradable films under drip irrigation on soil hydrothermal conditions and cotton (Gossypium hirsutum L.) yield, Agric. Water Manag. 213 (October 2018) (2019) 477–485, https://doi.org/10.1016/j.agwat.2018.10.036.
[83] G. Amare, B. Desta, Coloured plastic mulches: impact on soil properties and crop productivity, Chem. Biol. Technol. Agric. 8 (1) (2021) 4, https://doi.org/10.1186/s40538-020-00201-8.
[84] J.J. Stapleton, C.G. Summers, Reflective mulches for management of aphids and aphid-borne virus diseases in late-season cantaloupe (Cucumis melo L. var. cantalupensis), Crop Protect. 21 (10) (2002) 891–898, https://doi.org/10.1016/S0261-2194(02)00055-8.
[85] G. Vox, E. Schettini, Evaluation of the radiometric properties of starch-based biodegradable films for crop protection, Polym. Test. 26 (5) (2007) 639–651, https://doi.org/10.1016/j.polymertesting.2007.03.010.
[86] H. Khan, S. Kaur, T.C. Baldwin, I. Radecka, G. Jiang, I. Bretz, K. Duale, G. Adamus, M. Kowalczuk, Effective control against broadleaf weed species provided by biodegradable PBAT/PLA mulch film embedded with the herbicide 2-methyl-4-chlorophenoxyacetic acid (MCPA), ACS Sustain. Chem. Eng. 8 (13) (2020) 5360–5370, https://doi.org/10.1021/acssuschemeng.0c00991.
[87] M. Giaccone, C. Cirillo, P. Scognamiglio, M. Teobaldelli, A. Mataffo, A. Stinca, A. Pannico, B. Immirzi, G. Santagata, M. Malinconico, B. Basile, Biodegradable mulching spray for weed control in the cultivation of containerized ornamental shrubs, Chem. Biol. Technol. Agric. 5 (1) (2018) 1–8, https://doi.org/10.1186/S40538-018-0134-Z/FIGURES/4.
[88] A. Abduwaiti, X. Liu, C. Yan, Y. Xue, T. Jin, H. Wu, P. He, Z. Bao, Q. Liu, Testing biodegradable films as alternatives to plastic-film mulching for enhancing the yield and economic benefits of processed tomato in xinjiang region, Sustainability 13 (2021) 3093, https://doi.org/10.3390/SU13063093.
[89] R. Shine, Production of bio-degradable mulch film with innovating sowing solutions as the future for agriculture, Acta Hortic. 1252 (2019) 85–92, https://doi.org/10.17660/ActaHortic.2019.1252.11.
[90] A. Kalisz, A. Grabowska, A. Sekara, E. Capecka, A. Libik, K. Sulak, R. Jurkow, A. Kalisz, A. Grabowska, A. Sekara, E. Capecka, A. Libik, K. Sulak, R. Jurkow, Biodegradable polymers as floating row covers in field production of radish, Chil. J. Agric. Res. 79 (2) (2019) 243–256, https://doi.org/10.4067/S0718-58392019000200243.
[91] M. Kołodziejczyk, A. Oleksy, B. Kulig, A. Lepiarczyk, Early potato cultivation using synthetic and biodegradable covers, Plant Soil Environ. 65 (No. 2) (2019) 97–103, https://doi.org/10.17221/754/2018-PSE.
[92] H. Li, N. Kuang, Q. Gou, Y. Ma, Q. Li, Effects of different film mulches on photosynthetic characteristics and yield of summer maize (Zea mays L.) in the North China Plain, Arch. Agron Soil Sci. 67 (2) (2021) 179–190, https://doi.org/10.1080/03650340.2020.1718115.
[93] D. Zhang, Q. Wang, G. Li, X. Li, D. Sample, Optimum ridge width and suitable mulching material for sainfoin production with ridge–furrow rainwater harvesting in semiarid regions of China, Arid Land Res. Manag. 33 (3) (2019) 274–296, https://doi.org/10.1080/15324982.2018.1563241.
[94] J.S. Cowan, The Use of Biodegradable Mulch for Tomato and Broccoli Production: Crop Yield and Quality, Mulch Deterioration, and Grower's Perception, May, 2013.
[95] A. Kapanen, E. Schettini, G. Vox, M. Itävaara, Performance and environmental impact of biodegradable films in agriculture: a field study on protected cultivation, J. Polym. Environ. 16 (2) (2008) 109–122, https://doi.org/10.1007/s10924-008-0091-x.
[96] M.M. Moreno, A. Cirujeda, J. Aibar, C. Moreno, Soil thermal and productive responses of biodegradable mulch materials in a processing tomato (Lycopersicon esculentum Mill.) crop, Soil Res. 54 (2) (2016) 207–215, https://doi.org/10.1071/SR15065.
[97] P. Bucki, P. Siwek, I. Domagala-Swiatkiewicz, M. Puchalski, Effect of agri-environmental conditions on the degradation of spunbonded polypropylene nonwoven with a photoactivator in mulched organically managed zucchini, Fibres Text. East. Eur. 26 (2) (2018) 55–60, https://doi.org/10.5604/01.3001.0011.5739.
[98] R. Zong, H. Han, Q. Li, Grain yield and water-use efficiency of summer maize in response to mulching with different plastic films in the North China Plain, Exp. Agric. 57 (1) (2021) 33–44.
[99] V. Candido, T. D'addabbo, V. Miccolis, D. Castronuovo, Effect of different solarizing materials on weed suppression and lettuce response, Phytoparasitica 40 (2) (2012) 185–194.

[100] I. Kwiecien, G. Adamus, G. Jiang, I. Radecka, T.C. Baldwin, H.R. Khan, B. Johnston, V. Pennetta, D. Hill, I. Bretz, M. Kowalczuk, Biodegradable PBAT/PLA blend with bioactive MCPA-PHBV conjugate suppresses weed growth, Biomacromolecules 19 (2) (2018) 511–520, https://doi.org/10.1021/acs.biomac.7b01636.
[101] T.A.D. Oliveira, F.E.P. Mousinho, R. Barbosa, L.H.D. Carvalho, T.S. Alves, Mulch films based on poly(butylene adipate-co-terephthalate)/carnauba wax/sugar cane residue: effects on soil temperature and moisture, J. Compos. Mater. 55 (23) (2021) 3175–3190, https://doi.org/10.1177/00219983211011658.
[102] F.P. Neto, G. Souza, N. Fortes, A. Saraiva, R. Costa, E. Duarte, The role of mulching materials on Lactuca sativa production – Brazil case study, Acta Hortic. 1242 (2019) 139–145, https://doi.org/10.17660/ActaHortic.2019.1242.19.
[103] V. Hernández-Aranda, D. Rojas-Tortolero, J. Álvarez-Barreto, C. Arias-Vega, J. Proaño-Saraguro, A. Portalanza-Chavarria, D. Sosa, Characterization and use of a crop-residue-based mat mulch in the production of pepper (capsicum annuum) during dry season, Agronomy 11 (6) (2021) 1173, https://doi.org/10.3390/AGRONOMY11061173.
[104] J. López-Marín, C. Abrusci, A. González, J.A. Fernández, Study of degradable materials for soil mulching in greenhouse-grown lettuce, Acta Hortic. 952 (2012) 393–398, https://doi.org/10.17660/ActaHortic.2012.952.49.
[105] M.M. Hagner, T. Hyvonen, J. Mikola, R. Kemppainen, B. Lindqvist, T. Suojala-Ahlfors, K. Tiilikkala, Efficiency of a novel biodegradable pyrolysis liquid-amended mulch in weed control, Weed Res. 60 (3) (2020) 182–193, https://doi.org/10.1111/wre.12411.
[106] D. Zhang, Q. Wang, X. Zhou, Q. Liu, X. Wang, X. Zhao, W. Zhao, C. He, X. Li, G. Li, J. Chen, Suitable furrow mulching material for maize and sorghum production with ridge-furrow rainwater harvesting in semiarid regions of China, Agric. Water Manag. 228 (November 2019) (2020) 105928, https://doi.org/10.1016/j.agwat.2019.105928.
[107] R. Costa, A. Saraiva, L. Carvalho, E. Duarte, The use of biodegradable mulch films on strawberry crop in Portugal, Sci. Hortic. 173 (2014) 65–70, https://doi.org/10.1016/j.scienta.2014.04.020.
[108] F.I. Woodward, M.R. Lomas, C.K. Kelly, Global climate and the distribution of plant biomes, Phil. Trans. Roy. Soc. Lond. B Biol. Sci. 359 (1450) (2004) 1465–1476, https://doi.org/10.1098/RSTB.2004.1525.
[109] F.I. Woodward, M.R. Lomas, Vegetation dynamics – simulating responses to climatic change, Biol. Rev. 79 (3) (2003) 643–670, https://doi.org/10.1017/S1464793103006419.
[110] D. Briassoulis, Analysis of the mechanical and degradation performances of optimised agricultural biodegradable films, Polym. Degrad. Stabil. 92 (6) (2007) 1115–1132, https://doi.org/10.1016/j.polymdegradstab.2007.01.024.
[111] T. Kijchavengkul, R. Auras, M. Rubino, M. Ngouajio, R.T. Fernandez, Assessment of aliphatic-aromatic copolyester biodegradable mulch films. Part I: field study, Chemosphere 71 (5) (2008) 942–953.
[112] Y. Li, H. Feng, Z. Wang, Effect of Straw Pretreatment on the Soil Water-Holding Capacity and Evaporation in Low-Suction Section, Nature Environment and Pollution Technology 13 (3) (2014) 565–570. https://er.lib.k-state.edu/login?url=https://www.proquest.com/scholarly-journals/effect-straw-pretreatment-on-soil-water-holding/docview/1563754432/se-2?accountid=11789.
[113] Y. Zhang, J.H. Han, G.N. Kim, Biodegradable mulch film made of starch-coated paper and its effectiveness on temperature and moisture content of soil, Commun. Soil Sci. Plant Anal. (2008).
[114] Q. Tang, T. Lin, Z. Sun, A. Yan, J. Zhang, P. Jiang, F. Wu, H. Zhang, Effects of mulching film on soil microbial diversity and community of cotton, Amb. Express 12 (1) (2022) 33, https://doi.org/10.1186/s13568-022-01374-1.
[115] K. Suzuki, M.T. Noguchi, Y. Shinozaki, M. Koitabashi, Y. Sameshima-Yamashita, S. Yoshida, T. Fujii, H.K. Kitamoto, Purification, characterization, and cloning of the gene for a biodegradable plastic-degrading enzyme from Paraphoma-related fungal strain B47-9, Appl. Microbiol. Biotechnol. 98 (10) (2014) 4457–4465, https://doi.org/10.1007/s00253-013-5454-0.
[116] M.D. Orzolek, Introduction: history—north America, in: A Guide to the Manufacture, Performance, and Potential of Plastics in Agriculture, Elsevier, 2017, pp. 1–20, https://doi.org/10.1016/B978-0-08-102170-5.00001-4.
[117] Komariah, Pitaloka, D. D. A., Batubara, I., Nurcholis, W., Sandrawati, A., Setyawati, A., Syamsiyah, J., & Dewi, W. S. (2021). The effects of soil temperature from soil mulching and harvest age on phenol, flavonoid and antioxidant contents of Java tea (Orthosiphon aristatus B.). *Chemical and Biological Technologies in Agriculture*, *8*(1), 56. https://doi.org/10.1186/s40538-021-00256-1Komariah et al., (2021).
[118] M.S. Jahan, M.S. Dulal, C. Rajesh, H.M.S. Abul, S.H.U.S. Asma Akter, G.U. O. Shirong, Impacts of Plastic Filming on Growth Environment, Yield Parameters and Quality Attributes of Lettuce, Notulae Scientia Biologicae, 2018, https://doi.org/10.25835/nsb10410342.
[119] H. Jia, Z. Wang, J. Zhang, W. Li, Z. Ren, Z. Jia, Q. Wang, Effects of biodegradable mulch on soil water and heat conditions, yield and quality of processing tomatoes by drip irrigation, J. Arid Land 12 (5) (2020) 819–836, https://doi.org/10.1007/s40333-020-0108-4.
[120] X.B. Gu, Y.N. Li, Y.D. Du, Continuous ridges with film mulching improve soil water content, root growth, seed yield and water use efficiency of winter oilseed rape, Ind. Crop. Prod. 85 (2016) 139–148, https://doi.org/10.1016/J.INDCROP.2016.02.056.
[121] X. Zhao, J. Wang, K. Mei, Y. Leung, F. Wu, Color: an important but overlooked factor for plastic photoaging and microplastic formation, Cite This: Environ. Sci. Technol. (2022) 9161–9163, https://doi.org/10.1021/acs.est.2c02402.
[122] K. Fontenot, H. Kirk-Ballard, C.E.H. Coker, R. Strahan, I. Bacas, R.M. Ely, Assessing biodegradable mulch duration and nutsedge suppression during late summer cucumber production in Mississippi and Louisiana, Horticulturae 7 (9) (2021) 290, https://doi.org/10.3390/horticulturae7090290.
[123] M. Alamro, A. Mahadeen, O. Mohawesh, Effect of degradable mulch on tomato growth and yield under field conditions, Bulgarian J. Agric. Sci. 25 (6) (2019) 1122–1132.
[124] L. Ao, L. Qin, H. Kang, Z. Zhou, H. Su, Preparation, properties and field application of biodegradable and phosphorus-release films based on fermentation residue, Int. Biodeterior. Biodegrad. 82 (2013) 134–140, https://doi.org/10.1016/J.IBIOD.2013.02.009.
[125] X. Gao, D. Xie, Y. Huang, H. Zhang, M. Chen, The application effects of truly biodegradable mulch in potato farmlands, Agric. Sci. & Technol. 14 (2015) 7–10.
[126] A.I. Marí, G. Pardo, A. Cirujeda, Y. Martínez, Economic evaluation of biodegradable plastic films and paper mulches used in open-air grown pepper (capsicum annum l.) crop, Agronomy 9 (1) (2019), https://doi.org/10.3390/agronomy9010036.
[127] S. Ghimire, M. Flury, E.J. Scheenstra, C.A. Miles, Sampling and degradation of biodegradable plastic and paper mulches in field after tillage incorporation, Sci. Total Environ. 703 (2020), https://doi.org/10.1016/j.scitotenv.2019.135577.
[128] J.P. Warnick, C.A. Chase, E.N. Rosskopf, J.M. Scholberg, E.H. Simonne, R. L. Koenig, N.E. Roe, Hydramulch for muskmelon and bell pepper crop production systems, J. Veg. Sci. 12 (2) (2006) 39–55, https://doi.org/10.1300/J484v12n02_05.
[129] J.R. Goldberger, L.W. Devetter, K.E. Dentzman, Polyethylene and biodegradable plastic mulches for strawberry production in the United States: experiences and opinions of growers in three regions, HortTechnology 29 (5) (2019) 619–628, https://doi.org/10.21273/HORTTECH04393-19.
[130] K.J. Chen, T.L. Marsh, P.R. Tozer, S.P. Galinato, Biotechnology to sustainability: consumer preferences for food products grown on biodegradable mulches, Food Res. Int. 116 (2019) 200–210, https://doi.org/10.1016/j.foodres.2018.08.013.
[131] K. Khalid, A review of novel feedstock for the production of polylactic acid (PLA), Journal of Chemistry 2 (1) (2009).