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Review

Soil Bioplastic Mulches for Agroecosystem Sustainability: A Comprehensive Review

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Abstract: The use of plastic mulch films is widespread in agriculture for specialty cropping systems because of several benefits. In this article, we critically review, for the first time under a holistic approach, the use of biodegradable plastic mulches (BdPMs) in soil as a sustainable alternative to conventional petroleum-based plastics, highlighting the current state of understanding of their degradation in soil and their effect on soil microorganisms, weed control, and soil properties. In addition, we provide a detailed focus on the history and economic importance of mulching. BdPMs are effective for use in vegetable production in that they improve physical, chemical, and biological soil properties, as well as enhancing microbial biodiversity, controlling weeds, and maintaining soil moisture. BdPMs could be useful to limit the use of agrochemicals and reduce tillage and irrigation supplies for sustainable management.

Keywords: biodegradable mulching; biodegradation; soil microorganisms; soil health; weed management; sustainability

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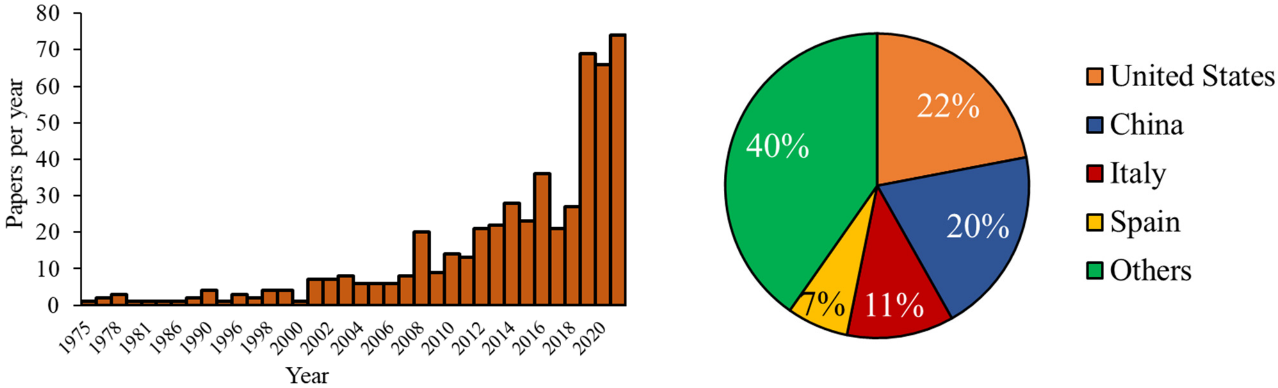
1. Introduction

The constant increase in the world population, together with environmental pollution and climate change, requires the development of innovative and sustainable techniques that meet human needs for food while respecting the environment. The search for bioplastic mulches in agriculture fits into this perspective. The terms “bioplastic” and “biodegradable plastic” are often used synonymously, but, strictly speaking, biodegradable plastics belong to the set of bioplastics. In fact, the latter are plastic materials which, depending on their origin and end-of-life behavior, are either bio-based or biodegradable, or both [1]. The setup of environmentally stable biodegradable plastics began in the 1990s [2] and, simultaneously, the scientific interest in biodegradable mulches has grown considerably over the years, as shown in Figure 1a. A query on Scopus® database inserting the words “biodegradable” and “mulch” in the search field “Article title, Abstract, Keywords” and limiting the search to the years from 1975 to 2021 resulted in 522 documents (Figure 1a). Figure 1a underlines a clear upward trend in the number of articles, especially in recent years. Indeed, the annual mean of published works in the three-year period 2019–2021 is 70, while the annual average of the previous three-year period (2016–2018) is 28 (Figure 1a). The countries that have made the greatest contribution of knowledge on biodegradable mulch are the United States, China, Italy, and Spain, which altogether accounted for about 60% of the works on the subject (Figure 1b).

A polymer is completely biodegradable when it is totally converted by microorganisms into carbon dioxide, water, minerals, and biomass, without any harmful substances. However, the acceptable time for biodegradation and its measurement has been a matter of debate, as almost all carbon-based materials are biodegraded sooner or later [3], this does not mean that all carbon-based materials can be considered biodegradable. The EN 17033 European standard on biodegradable mulch film, issued in 2018, is the result of a long debate and establishes the requirements for biodegradable mulching films, manufactured with thermoplastic materials. According to the standard, a film material is considered biodegradable if it reaches a minimum mineralization rate of 90% in a test period not exceeding 24 months [4]. Before biodegradation can occur, plastic must be colonized by microorganisms, evolving enzymes to degrade it into assimilable carbon sources. Plastic-degrading organisms have been discovered in habitats ranging from insect digestive tracts [5] to recycling plants to the open ocean [6]. Interestingly, they vary widely in substrate scope, depolymerization mechanism, and degradation efficiency [7].



(**a**) (**b**)

Figure 1. (**a**) Number of papers and (**b**) distribution by country of papers published from 1975 to 2021 on biodegradable mulches. Source: Scopus®.

Although several review articles have been published concerning bioplastic (BP) mulches, a critical and comprehensive review is still lacking. The purpose of this review is to provide an overview of the effects of biodegradable mulches on soil as an ecosystem, weed control and soil properties, all within a framework in which aspects such as the importance and the issues of mulches in agriculture, together with the materials they are made of, are brought into focus. The literature review was performed using a systematic bibliographic search on the Scopus, Web of Science, PubMed, and Google Scholar databases with the topic keywords. The bibliographic search about the history of biodegradable mulching was conducted by directly consulting historical sources and documents. Overall, 165 items were cited, including 65 research articles, 68 reviews, 16 books or book chapters, five conference papers, two dictionaries, two informative articles, three reports, and four websites.

2. General Background of Mulching

2.1. History and Economic Importance

The English word "mulch" could be a loanword of the early modern age (XVI century) German word "mölsch" (soft or rotten). The two words could be also related, that is to say they could have the origin in common [8]. Finally, "mulch" could derive from Middle Dutch "malsc" [8]. The Proto-Indo-European root of the word could be "mel-" meaning "soft", with derivatives referring to soft or softened materials [9]. "Mel-" may be the source of the Greek "malakos" (soft) and the Latin "mollis" (soft) [9]. Although the etymology of the word "mulch" recalls the idea of softness, the mulching technique was also implemented with lithic materials such as stones, pebbles, and volcanic sand [10]. Lithic mulching is an ancient technique typical of agriculture in arid and semi-arid areas, and human communities distant in time and space have resorted to it from prehistoric times to the present day, and on all continents [10]. Reading the texts of the modern age, it is possible to find information about the use of plant materials to cover the soil. Giovan Vettorio Soderini, an Italian agronomist of the sixteenth century, in his "Trattato della coltivazione delle viti, e del frutto che se ne può cavare" (published in Florence in 1600), recommended placing the mulch inside the pit to plant vines. François Gentil in his "Le jardinier solitaire" (published in Paris in 1704), indicated a practice that might appear singular; he advised placing straw mulch at the foot of the trees, so that their fruits would not be damaged by falling to the ground. In the November 1778 issue of *Farmer's Magazine* (a periodical published in London), regarding the seed propagation of rhubarb, it is written: *If the seeds vegetate late in the season, they ought to be covered with mulch or moss, to preserve them in winter.* Since the early twentieth century, the attention of farmers towards mulching, made with both vegetable residues and paper, has increased [11]. In this regard, the use of tar paper as mulch began long before polyethylene (PE) was available. In fact, the first tar paper mulch, designed to defend the roots of trees from pests, dates back to 1870 [12]. In the first half of the twentieth century, some crops, such as the pineapple in Hawaii [13], have been enhanced through the innovation of paper mulching. Interest in mulching has further grown with the development of plastic materials [11]. In 1948 in the United States, PE was evaluated for the first time in agriculture with the aim of making greenhouse covers cheaper than those made with glass. However, the use of PE films as mulch began in the early 1960s when mulch applicators were developed, together with transplanters that plant directly on the mulch [14]. The use of plastic in agriculture increased considerably over the years, so much so that the word "plasticulture" was coined as a blend of the words "plastic" and "agriculture". In this regard, at the end of the 1980s more than 3.5 million hectares were covered with plastic mulch (Figure 2) and nearly 450,000 tons of plastic mulch were used every year [14]. In the same period, about 80% of the mulched areas were in China (Figure 2). This figure appears even more surprising if considering that in 1979 only 44 hectares of mulched area were in China [14]. In the 1999–2002 period, China still had about 80% of the world's mulched areas, despite the latter having grown to nearly 12.5 million hectares [15,16]. In 2017, the areas covered by plastic mulch reached 22 million hectares [17], 84% of which were in China [18] (Figure 2).

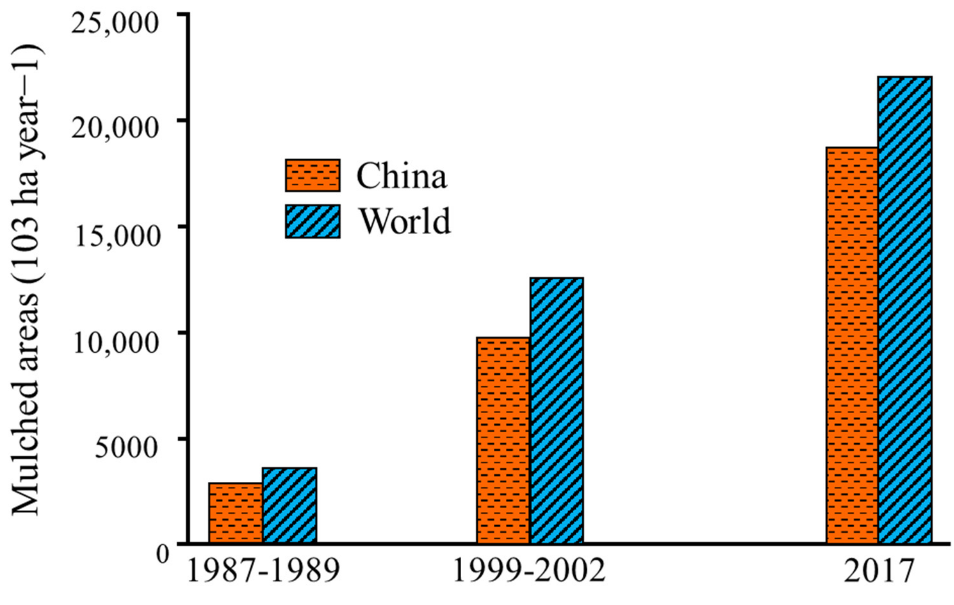


Figure 2. Mulched areas in China and in the world over the 1987–2017 period. Sources: Jensen and Malter [14]; Jouet [15,16]; Castellón [17]; An et al. [18].

Furthermore, in 2017 about 2.75 million tons of mulch film were used in the agricultural sector [19], meaning that over just thirty years the world annual consumption of plastic films increased sixfold. Plasticulture is still very widespread in Europe. In the two-year period 2018–2019, plastic mulches accounted for 25.3% of the plastic sold for crop production and for 11.2% of the total plasticulture in Europe (Figure 3) [20]. The European countries (EU + 3) where the most plastic films were sold in 2018 were Spain (93,000 tons) and Italy (89,500 tons), followed by Germany and France (70,000 and 57,500 tons, respectively) (Figure 4) [20].

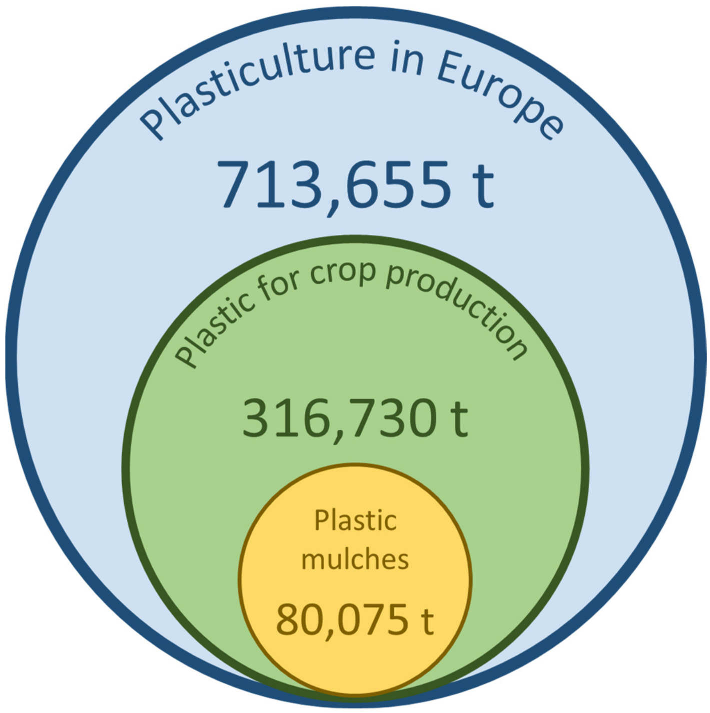


Figure 3. Venn diagram about plasticulture in Europe over the 2-year period 2018–2019. Data are expressed as tons of plastic sold. Source: APE Europe [20].

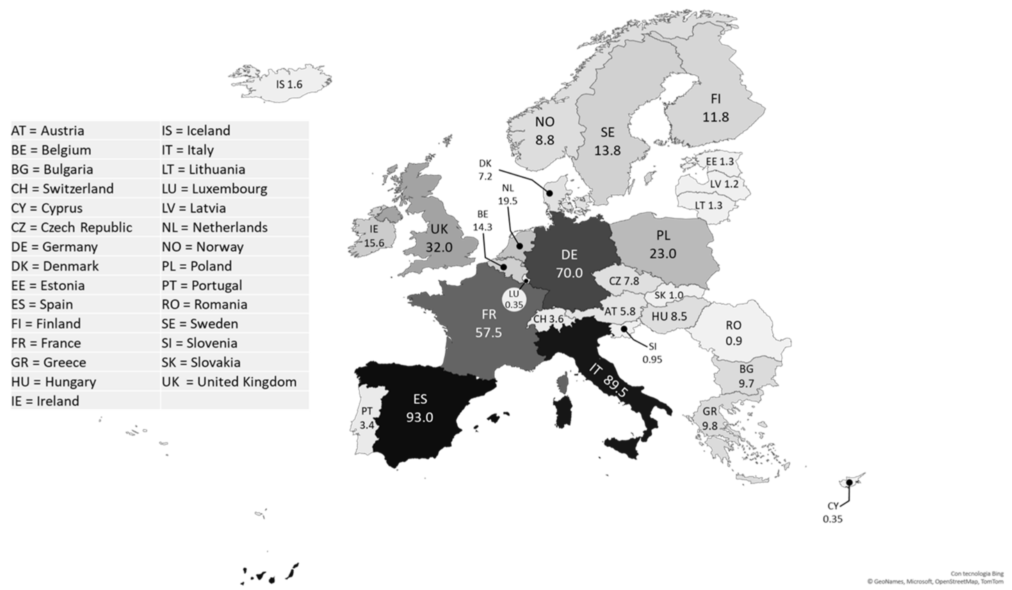


Figure 4. European film sales by country in 2018 expressed as thousands of tons. The darkness of each country in the map is proportional to the mass of plastic films sold. The two-letter abbreviations of country names are in accordance with the ISO 3166-1 alpha-2 standard. Source: APE Europe [20].

2.2. Classification of Mulching and Main Issues

Mulches can be defined as materials that are applied or grow on the soil surface (the latter are the living mulches), in contrast to soil-incorporated materials [21]. They may provide many services to the soil: improvement of moisture content, reduction in soil compaction and erosion, mitigation of temperature excesses and defects, and improvement to plant establishment and growth [22,23]. Not to mention, organic and living mulches can improve soil nutrition, degrade pesticides, and reduce weed pressure [21,24–27]. Mulching materials can be classified into three types: organic materials (products of vegetable or animal origin), synthetic materials, and special materials (e.g., gravel); they can be used in combination, based on the specific aims [28]. Figure 5 shows the variety of mulches in relation to the material they are made of. There are a great number of organic mulches, and these include agricultural and industrial wastes, as well as living mulches. Synthetic mulches include several types of plastic films (Figure 5), even biodegradable and photodegradable ones [3], as well as spray-degradable polymer films (Figure 5), which are very versatile and easy to apply in the field.

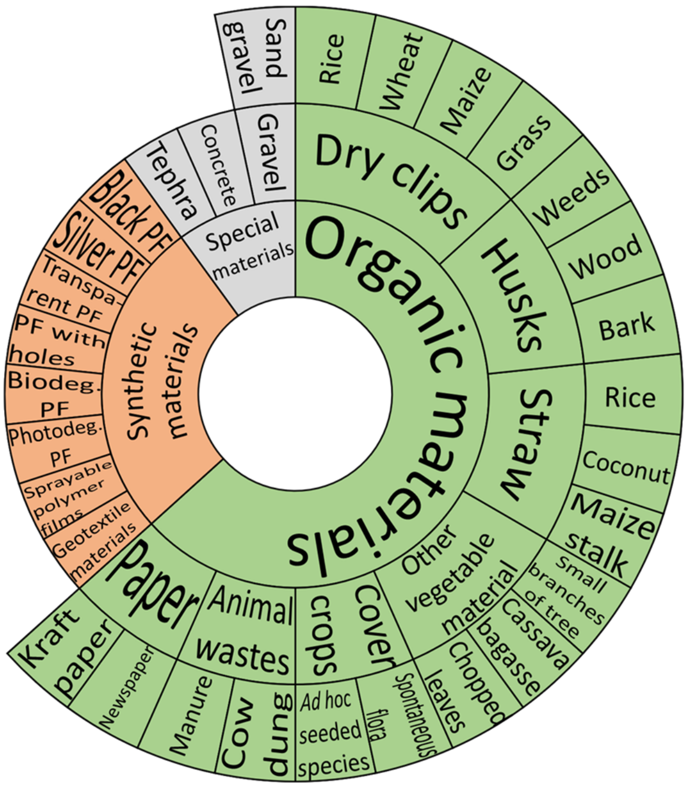


Figure 5. Mulches divided into classes of materials. Modified and adapted from Kader et al. [28]. PF: plastic film.

The choice of mulching material depends on several intersecting factors such as cost, availability, ease of application, local climate, and agronomic needs of the main crop [29,30]. The color of the plastic films, for example, affects solar radiation transmittance and thus soil temperature [31], but also influences other aspects, such as the attraction of specific insects and the control of pathogens [22]. The climatic conditions of the cultivation area must also be considered when choosing the mulching method [28]. The large-scale production of plastic films and the high persistence of the latter in the environment have raised alarms about a potential massive accumulation of pollutants in the environment [23]. Furthermore, the residues of plastic films left in the soil over time fragment and become smaller and smaller, to the point of becoming microscopic, i.e., “microplastics” [32]. Therefore, plastic films must be removed to prevent them from becoming a threat to terrestrial and aquatic fauna when they enter the food chain [23]. Plastic mulches can be recycled, however; during mechanical recycling, the films go through several stages: washing, shredding, drying, and pelletizing [33]. Obviously, all these operations have a cost. According to Le Moine and Ferry [34], the environmental issues associated with plastic mulching are aggravated by the fact that, over the years, the thickness of the films has decreased from 40 to 20 μm, then to 10 μm and even below. When they were thicker, these films were easier to recycle. Now that they are thinner, they become dirtier and therefore more difficult to recycle.

3. Plastic Mulch Materials

3.1. Polymers and Plastics

A polymer, the term for which derives from the Greek words πολυ- (poly) and μέρος (meros), literally meaning "having many parts", is a substance composed of macromolecules. Polymers are present in nature, since they make up tissues of living organisms or perform important biochemical functions (e.g., cellulose and proteins), and some of these have important technological applications [35]. There are also polymers of partial natural origin that are synthesized from living tissues and chemically modified into "half-synthetic polymers". Totally synthetic polymers, synthesized from low-molecular components, i.e., organic monomers [36], are mostly produced from fossil fuels such as oil and gas. Plastics are polymers that can be grouped into bioplastics and conventional plastics. The word "bioplastic", however, can cause confusion, due to the meaning that everyone can attribute to the prefix "bio". In fact, according to European Bioplastics [1], a plastic material is defined as a bioplastic (BP) if it is either bio-based (i.e., wholly or partially derived from biomass), biodegradable, or features both properties (Figure 6). Thus, contrary to common sense, some petroleum-based plastics can also be classified as bioplastics, provided they are biodegradable (Figure 6).

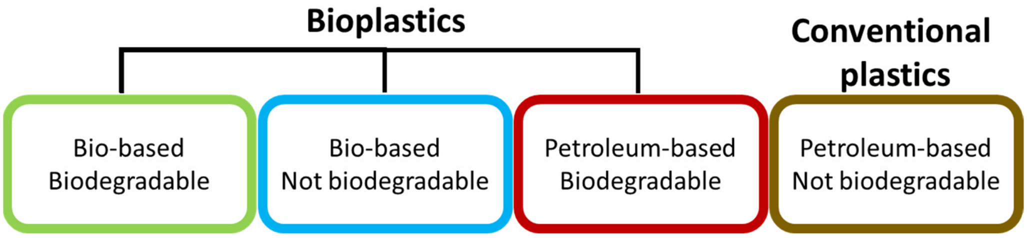


Figure 6. Classification of plastics according to origin and biodegradability.

3.1.1. Conventional Petroleum-Based Plastics (CPs)

Conventional petroleum-based plastics (also called fossil-based plastics) are artificial organic polymers, obtained from natural gas or oil, and utilized in contemporary society in every aspect of daily life [37]. One of the products of crude oil distillation is naphtha, which in turn can be transformed into various hydrocarbons by thermal cracking and fractionation. The thermal cracking of saturated hydrocarbons produces unsaturated hydrocarbons, which are molecules suitable for use as monomers in polymerization reactions [36]. Around 4% of global oil and gas extracted is employed as raw material for plastics production, and a similar amount is used as energy in the process [38,39]. Among the environmental impacts caused by plastics production, greenhouse gas (GHG) emissions are of central importance. It suffices to know that plastics caused 4.5% of global greenhouse gas emissions in 2015; moreover, 6% of global coal electricity is used for plastics production [40]. The most-used CPs in agriculture are: polyethylene (PE), polypropylene (PP), ethylene-vinyl acetate (EVA), polyvinyl chloride (PVC), polycarbonate (PC), and polymethylmethacrylate (PMMA) (Table 1). Some of these materials are suitable as greenhouse covers (PC and PMMA) (Table 1). PVC is used to produce irrigation pipes due to its mechanical and chemical resistance. One of the most-used polymers for the covering of small tunnels is EVA, due to its transparency and thermal insulation effect [41]. PP is used to produce pipes, nets, sheets, twines [42] (Table 1) and, as a valid alternative to PE, mulches. Compared to those made of PE, PP mulches have a lower impact resistance, but a higher service temperature and a greater tensile strength. PP is also more durable than PE; therefore, it is more suitable in perennial systems where mulch remains or is reused for several years [43]. However, the most common CP mulches are those made of PE and, more precisely, those made of low-density PE (LDPE). LDPE and high-density PE (HDPE) have the same composition, both being made up of C_2H_4, but they differ in structure. In fact, HDPE has a linear structure and no or a low degree of branching, while LDPE has a higher degree of short and long side-chain branching [44].

Table 1. Characteristics and purposes of the most-used petroleum-based plastics in agriculture. Adapted and modified from Scarascia-Mugnozza et al. [42]. LDPE: low density polyethylene; HDPE: high density polyethylene; PP: polypropylene; EVA: ethylene vinyl acetate; PVC: polyvinyl chloride; PC: polycarbonate; PMMA: polymethylmethacrylate.

Property/Purpose	Material						
	LDPE	HDPE	PP	EVA	PVC	PC	PMMA
Chemical formula	$(C_2H_4)n$		$(C_3H_6)n$	$(C_2H_4)n(C_4H_6O_2)m$	$(CH_2CHCl)n$	$(C_{16}H_{14}O_3)n$	$(C_5H_8O_2)n$
Monomer molar mass (g mol^{-1})	28.05		42.08	114.14	62.50	254.28	100.12
Density ρ (kg m^{-3}) (ISO 1183)	$910 \leq \rho \leq 925$	$940 \leq \rho \leq 965$	$850 \leq \rho \leq 900$	$926 \leq \rho \leq 950$	$1370 \leq \rho \leq 1430$	$1200 \leq \rho \leq 1220$	$1170 \leq \rho \leq 1200$
Fertilizer bags	✓	✓					
Greenhouse coverings	✓			✓	✓	✓	✓
Irrigation and drainage	✓	✓	✓		✓		
Low tunnel films	✓			✓	✓		
Mulching films	✓		✓				
Nets for collecting		✓	✓				
Nonwoven/floating covers	✓		✓				
Other (rigid sheets, pots, twine, etc.)	✓	✓	✓		✓		✓
Silage films and protective covering	✓						
Vineyard and orchard coverings	✓			✓			
Woven nets (hail, wind, bird, shade)		✓					

Plastics usually contain more than one added component. If the added material is another polymer, then it is a polymer blend. There are many additives and fillers that can be compounded into the polymers for various purposes [36]. Non-ionic surfactants (esters of fatty acids and glycerine or sorbitan) are used as anti-fogging additives in the antifog films in order to allow condensation to spread into a continuous and uniform transparent water layer on the surface of films. This results in improved light transmission and transparency. Photoselective antipest films opaque to ultraviolet light are obtained with UV-absorbing additives. To improve the IR opacity of LDPE films, fillers or additives are used, especially of mineral type, such as silicates, carbonates, sulfates, and hydroxides, etc. [41]. Pigments can be used as additives in the production of plastic mulches to make them colored or black [42]. Additives can aggravate environmental problems related to plastics. In this regard, the case of phthalates (PAEs) in China is noteworthy. PAEs are broadly added to plastics in order to enhance their plasticity and versatility. Given that they are not chemically bound to the polymeric chains, PAEs can easily migrate from products and be released as xenobiotic and hazardous compounds into the environment [45]. It is an established fact that the application of plastic mulches is one of the major sources of PAEs in China's soils [45].

3.1.2. Bioplastics (BPs)

The world production of bio-based polymers amounted to 3.5 Mt in 2018 [46], 3.8 Mt in 2019, and 4.2 Mt in 2020 [47]. A constant growth is therefore observed; however, these values represent roughly 1% of the annual world production of fossil-based polymers. Based on the observed growth trend, the quantity of bio-based polymers produced in 2025 is expected to be 6.7 Mt [47]. In 2020, a small fraction (0.038%) of the biomass produced in the world was demanded for bio-based polymers production. This fraction amounts to about 4.8 Mt and is divided as follows: 37% are made of glycerol, 24% of starch, 16% of sugars, 12% of non-edible plant oil, 9% of cellulose, and 2% of edible plant oil (Figure 7) [47]. The percentage of agricultural land used in the production of biomass destined for bio-based polymers is 0.006% [47], a percentage that is six times lower than the above-mentioned 0.038% relative to the share of biomass. This disproportion has two explanations. On the one hand, more than a third of the feedstocks (37%) is represented by glycerol (Figure 7), which is a by-product of biodiesel production and is therefore obtained without land use [47]. On the other hand, starch and sugars, which represent, respectively, 24% and 16% of the total feedstocks (Figure 7), come from high yielding crops [47]. However, from the 4.8 Mt of feedstocks, only 1.9 Mt of bio-based components are obtained, while the rest (2.9 Mt) are made up of losses of feedstock and intermediate products, together with waste products (Figure 7) [47]. From 1.9 Mt of biobased components 4.0 Mt of bio-based structural polymers (completely or partially bio-based) were obtained in 2020 (Figure 7) [47].

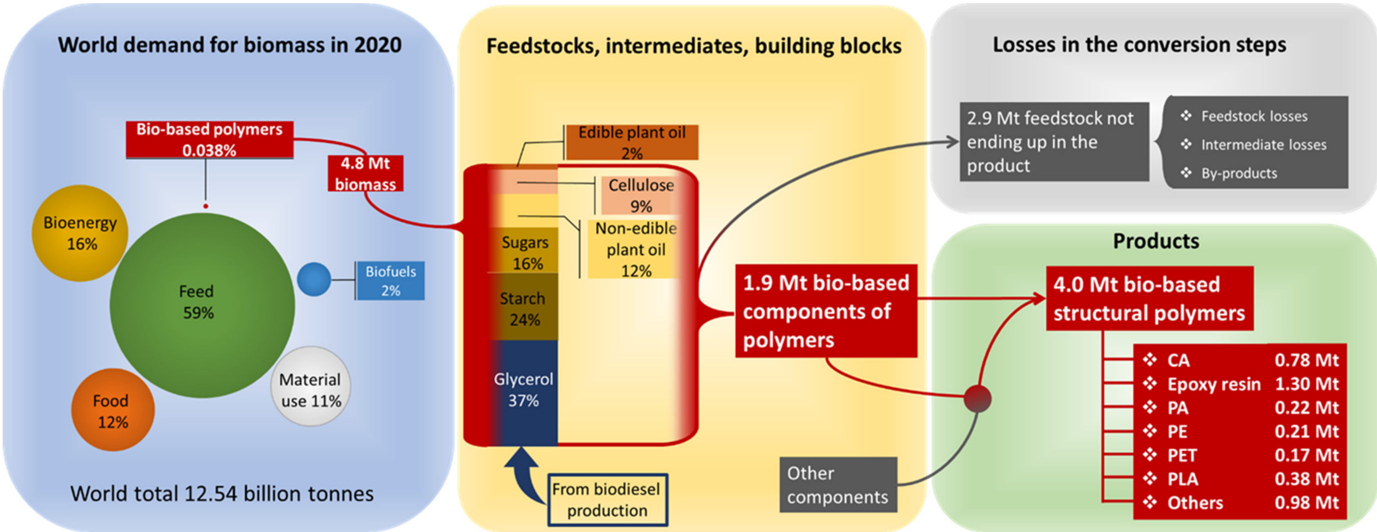


Figure 7. Diagram of the relationships between the biomass to produce bio-based polymers and bio-based structural polymers produced worldwide in 2020. Modified and adapted from Carus [47]. CA: cellulose acetate; PA: polyamide; PE: polyethylene; PET: polyethylene terephthalate; PLA: polylactic acid.

As seen above, an important part of bio-based plastics derives from agricultural raw materials, which compete with food production for arable land, water, and other resources [48]. Furthermore, bio-based plastics can have a certain environmental impact. In fact, their production cause acidification and eutrophication, as their raw materials are obtained using inputs such as pesticides, herbicides, and fertilizers [49].

Below is an overview of the most common BPs employable as feedstocks to produce mulches.

Starch is a plant reserve carbohydrate, synthesized from glucose, which in turn is produced through photosynthesis from carbon dioxide and water. For this reason, it is a biodegradable, renewable, and inexpensive raw material. However, starch has poor physical properties, since it is a hydrophilic substance that dissolves in water and becomes brittle when it is dried. It is therefore necessary to mix or change the composition of the starch before it can be used as a biodegradable mulching material [50]. There are mulching films based on starch mixed with biodegradable polyesters to improve their mechanical characteristics, while maintaining their biodegradability.

Along with starch, aliphatic polyesters are the most widely used bio-based feedstocks to produce biodegradable plastic mulches. The aliphatic polyesters are polymers suitable for use as biodegradable plastics, thanks to the ease with which they are degraded by lipolytic enzymes and microorganisms [51].

Polyhydroxyalkanoates (PHAs) are a family of biological polyesters consisting of 3-hydroxyalkanoic acids (HA) as monomer units. PHAs have been studied as possible substitutes for CPs, since they can be synthesized and degraded by living organisms [52]. The properties of PHAs depend on the composition of their monomers. There are, in fact, short-chain HA (3–5 carbon atoms), medium-chain HA (6–14 carbon atoms), and long-chain HA (more than 14 carbon atoms) [53]. Moreover, PHAs can be homopolymers (i.e., consisting of the repetition of the same monomer) or heteropolymers (i.e., consisting of different monomers). Finally, with respect to their origin, it is possible to distinguish natural PHAs, semi-synthetic PHAs and synthetic PHAs [54]. PHAs are synthesized by Gram-positive and, especially, Gram-negative bacteria [53]. However, the production of PHA by microorganisms in bioreactors poses technical problems that limit its economic convenience. On the other hand, the biosynthesis carried out by transgenic plants, which only need water, mineral salts, CO_2, and light, makes the production of PHAs more economical and respectful of the environment. Furthermore, plants, unlike bacteria, do not degrade PHAs [55]. Despite that more than 150 types of PHA have been obtained [56], there are few mulching films based solely on PHAs on the market, probably due to the high costs of production and poor mechanical properties [57]. Fortunately, one of the valuable characteristics of PHAs is their compatibility with other polymers (especially polylactic acid), with which they can form the so-called polymer alloys [58].

Polylactic acid (PLA) is another bio-based and biodegradable polymer used in agriculture. The molecular brick of which PLA is made is lactic acid (LA), a hydroxy acid that exists in both the dextrorotatory and levorotatory forms. The main feeds of LA-producing bacteria are glucose and maltose from wheat, potatoes, sugar-beets, corn, and sugarcane molasses [59]. The production of PLA passes through some stages that can be summarized as follows: obtaining LA by lactic fermentation or by chemical synthesis, LA transformation into lactide monomers, and polymerization of lactide monomers [60]. PLA possesses good mechanical strength and, compared to other biopolymers, it is less expensive and available in larger quantities. However, it has characteristics that make it unsuitable for mulch on its own [61]. In fact, the glass transition temperature (~60 °C) of PLA makes it not easily accessible to microorganisms under normal conditions of use [61]. Additionally, PLA is quite hard, resulting in embrittlement and poor thermostability [61]. Fortunately, PLA is compatible with other polymers, such as PHAs. The blend of PLA and PHAs creates a synergistic effect, due to the complementarity of their respective characteristics [58]. Biodegradability of PHA/PLA mulches prepared using both spunbound and meltblown processing have been evaluated [62,63]. The results indicate that spunbond mulches biodegrade more slowly than meltblown ones, suggesting that the former are more suitable for making longer-lasting products, such as row covers and landscape fabrics [62,63].

There is also **bio-based PE**, obtained through the polymerization of ethylene produced with the catalytic dehydration of bioethanol [64], but unfortunately it is not biodegradable [48].

The most common fossil-based polymers used to make biodegradable plastic mulch are **poly(butylene-adipate-co-terephthalate) (PBAT)**, **poly(ε-caprolactone) (PCL)**, and **poly (butylene succinate) (PBS)** [65]. PCL and PBS are aliphatic polyesters (such as PHAs and PLA [2]); the former has a relatively low melting point (60 °C) and is often mixed with starch to increase biodegradability, while the latter has physicochemical properties like polypropylene's [65]. PBAT has a high elasticity and mechanical strength, as well as resistance to water and oil [65]. Its biodegradability in soil has been demonstrated using ^{13}C-labeled PBAT, which made it possible to distinguish the CO_2 produced by the mineralization of the soil organic matter from that resulting from the degradation of the polymer. It was also possible to recognize the ^{13}C in the microbial biomass of the soil [66].

Protein-based mulching films combine biodegradability with N content, which increases their agronomic value; another advantage is the fact that they can be blended with other polymers [67]. They can be of animal origin, such as the mulching sprays obtained from protein hydrolysates, derived from waste products of the leather industry [68], or can be derived from the proteins that make up the body of scavenger insect larvae, which live on decaying organic matter [69]. Both products would fall within the scope of the circular economy. The protein-based films can also be of plant origin; for example, the secondary product resulting from the extraction of oil from soy is a protein-rich flour that can be used as a raw material to produce such films [70]. Unfortunately, soy protein-based films are brittle and water sensitive and therefore require plasticizers, such as glycerol and graphene, to improve their mechanical properties [70,71]. Zein is a hydrophobic, alcohol-soluble protein isolated from corn. It is a thermoplastic material very suitable for film production and can be used to make food packaging [72]. Zein-based mulching films have been evaluated as a possible economic and environmentally friendly alternative to polyethylene mulching, with reference to soil water losses by evaporation on greenhouse-grown tomatoes [73].

Paper mulches were included here, although cellulose is not a bioplastic, to complete the framework of mulches that are bio-based and/or biodegradable. The main raw material of paper mulches is vegetable fibers, but research on traditional paper mulches currently focuses on reinforcing agents that can affect mulch performance [12]. The conventional papermaking process results in mulches with insufficient mechanical properties to meet application requirements in the field. It is true that the performance of paper mulch can be improved by chemical additives, but it is equally true that the latter increase the cost of the product up to making it applicable only to highly profitable crops. Furthermore, such substances can have a negative environmental impact [12]. The performance of traditional paper mulch can be improved through solution impregnation, with which composite coated paper is obtained. Research on paper mulches has also extended to paper production processes, such as the non-woven technology papermaking process, which uses mineral fibers, plant fibers, and chemical fibers as raw materials [12]. Paper mulches are much more biodegradable than plastic ones, but this virtue must be accompanied by lower costs and improved performances if the paper is to spread as mulch in different environmental conditions.

4. Biodegradable Plastic Mulches' (BdPMs) Degradation in Soil

4.1. Abiotic Degradation

BdPMs can undergo bulk erosion, characterized by degradation starting from cross sections, since water can spread through the polymer in amorphous regions, triggering hydrolysis that cleaves chemical bonds and thus causing a rapid reduction in molecular weight [74]. Mulching films are subjected daily to UV rays, inducing photo-oxidation, which accelerates the fragmentation of polymers without leading them to the complete degradation [75]. However, photo-oxidation does not prevent BdPM biodegradation. Indeed, the reduction in molecular weight and the formation of oxygenated structures can accelerate the degradation process. The resistance of mulching films to photo-oxidation can be increased or decreased with the use of additives [75]. In general, BdPMs have low photoresistance and therefore their photo-oxidation is faster than that of conventional plastic mulches [76]. PLA and PBAT are biodegradable polymers with different responses to photo-oxidation. In fact, the UV radiation in PLA causes chain scission, with a consequent reduction in molecular weight, whereas, in PBAT, UV radiation results in polymeric chain crosslinking, with an increase in molecular weight, which, however, does not cause an increased resistance to biodegradation [77]. Other abiotic factors typical of agriculture contributing to the degradation of plastic films are heat, pollutants, and wind [78]. Atmospheric precipitation also contributes to the loss of polymer integrity, especially during high-intensity events such as hail [79].

4.2. Biodegradation by Bacteria and Fungi

According to the American Society for Testing and Materials [80], the biodegradation of plastics is the process by which polymeric material is decomposed into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms. However, most polymers are insoluble in water, and they cannot therefore be absorbed directly by microorganisms. For this reason, BdPM biodegradation includes several steps: (1) biodeterioration, consisting in the fragmentation into small parts; (2) depolymerization, i.e., the cleavage of the polymer chains into oligomers, dimers, and monomers by means of enzymes and free radicals; (3) assimilation, in which some of these molecules are used in microbial metabolism; (4) and finally mineralization, with the release into the soil of simple molecules such as CO_2, N_2, CH_4, and H_2O [81]. BdPMs can undergo surface erosion carried out by microorganisms that consume polymers from the outer surface through the production of enzymes, thus causing an early but slow reduction in molecular weight [74].

Bacteria, fungi, and algae recognize polymers as nutrient and energy sources. Several groups of bacteria are important in the biodegradation process including *Bacillus* (able to produce thick-walled endospores that are resistant to heat, radiation, and chemicals), *Azotobacter, Klebsiella, Pseudomonas, Actinomycetes, Nocardia, Streptomyces, Thermoactinomycetes, Micromonospora, Mycobacterium, Rhodococcus, Flavobacterium, Comamonas, Escherichia,* and *Alcaligenes Microbacterium*; some of these bacteria can accumulate polymer up to 90% of their dry mass [82,83]. Mulching films' biodegradation can also be performed by soil fungi, of which the most active belong to the following taxa: *Sporotrichum, Talaromyces, Phanerochaete, Ganoderma, Thermoascus, Thielavia, Paecilomyces, Thermomyces, Geotrichum, Cladosporium, Phlebia, Trametes, Candida, Penicillium, Chaetomium* and *Aerobasidium.* For in situ mulching film degradation, there are several examples of both ascomycetes and basidiomycetes fungi with effective hydrolytic and oxidative mechanisms. A recent review conducted by Sanchez [84] lists about 25 studies in which the fungal degradation of petroleum-based polymers was analyzed. Another study on PE degradation by a fungus, *Penicillium simplicissimum* YK, is reported by Yamada-Onodera et al. [85]. The efficiency of PE degradation depended on the growth phase in pure cultivations of the fungus. Functional groups inserted into PE aided biodegradation. Polyethylene with starting molecular weights of 4000 to 28,000 had lower molecular weights after 3 months of liquid cultivation with the hyphae of the fungus. The degradation by fungi may reduce or eliminate the need for a physical pretreatment of plastics even if the fungal activity alone leads to a limited degradation of the polymer [86].

Some microorganisms have been demonstrated to be suitable for the biodegradation of specific BPs. In this regard, Mergaert et al. [87] found that *Acidovorax facilis*, *Variovorax paradoxus,* and *Streptomyces* sp. are the most important bacteria in the soil biodegradation of PHAs. The same authors found that *Aspergillus fumigatus*, *Paecilomyces marquandii,* and *Penicillum* sp. are the most active fungi in PHAs' soil biodegradation. P(3HB), a polymer belonging to the PHAs family, is degraded by at least 80 taxa of microorganisms (57 bacteria and 23 fungi) isolated from different environments, such as soils, compost, natural waters, and sludge [88]. PLA-degrading microorganisms are not widely distributed, so PLA is less susceptible to microbial attack compared to other BPs [89]. However, some microorganisms showed effectiveness in PLA biodegradation, such as many strains of the *Amycolatopsis* and *Saccharotrix* genera. Regarding enzyme activity, proteinase K from *Tritirachium album* and lipase from *R. delemar* were shown to be effective in degrading PLA [51]. Unlike PLA, PCL-degraders are widely distributed in different environments. Some fungi are very effective in degrading PCL, such as *Penicillium* sp. and *Aspergillus* sp. [51], whereas the lipases of *R. delemar* and *R. arrhizus* showed an effective activity in PCL hydrolysis [90].

4.3. Biodegradation Methods

Several methods are reported to assess the rate of plastic mulches' degradation in field conditions, such as the estimation of material weight loss over time, and photographic and subsequent monitoring analysis using image processing programs [91]. Visual aspects are also used to describe the degradation of the plastic film in field conditions, such as roughening of the surface, formation of holes, fragmentation, or color changes. Monitoring is often carried out by numerical qualitative scales that evaluate the degree of soil cover or the film resistance. These qualitative scales can be linked to quantitative tests, both in field and laboratory conditions. In the laboratory, the degradation of mulch films has been studied according to mechanical and optical aspects by microscopy and the evolution of CO_2/O_2 consumption ratio, the amount of carbon assimilated by the microbial community (CO_2 issued), or by enzymatic soil measures [92]. Unfortunately, hydrophobic BdPMs can adsorb pesticides, causing their accumulation. The mechanisms of pesticide degradation in soil are similar to those that occur in composting, but the latter involves higher temperatures, more organic matter and more intense biological activity [93], with the result that the degradation of pesticides by composting is effective, with some exceptions [94]. On the other hand, the lack of oxygen and the high temperatures typical of composting create the optimal conditions for BdPMs to be degraded by thermophilic microorganisms [95], unlike the soil, where aerobic conditions and mesophilic temperatures prevail [96]. Therefore, composting represents a possible solution to the double problem of disposing of BdPMs and the pesticides adsorbed on them.

5. Effect of BdPMs on Soil Microorganisms and Their Activity

BdPMs can improve the rhizosphere micro-environment as a result of the improved soil temperature and moisture. The microbiome living in the rhizosphere plays a key role as regards plant growth, development, and yield. Different kinds of microorganisms including proteobacteria and N-fixing bacteria, essential for plant growth, have been identified in the rhizosphere. Similarly, it is possible to find chemical compounds such as nematocidal amino acids (cristationin and homoserine), carbohydrates (fructose) stimulating microbial growth, and sterols (sitosterol) regulating plant development [97]. In addition to soil microorganisms, several allelochemicals have been reported to interfere with plant growth and ecosystem maintenance [98,99]. There are billions of microbial cells in a gram of soil [100], varying based on root zone, crop species, the vegetative phase, or the presence of stress and/or disease [101–103].

Moreover, fungi thrive in the soil thanks to their great ability to adapt to different pedoclimatic conditions and resilience in overcoming different stress types [104]. Specifically, the arbuscular mycorrhizal fungi play a key role because they are commonly associated with improvements of crop yields [105], nutrient cycle, soil structure, and plant tolerance to biotic and abiotic stresses. The main groups of rhizospheric bacteria belong to *Bacillus*, *Proteobacteri*a, *Acidobacteria,* and *Actinobacteria* genera [106,107]. *Proteobacteria* represent the most abundant group in the rhizosphere due to their ability to positively respond to the presence of labile C, thus showing rapid growth and adaptability [108]. The Acidobacteria are the second group by abundance in the rhizosphere and play a decisive role in the C cycle, as they degrade lignin and cellulose [109]. Archaeobacteria constitute the third most popular group and, according to Buée et al. [110], can survive even in environments with low oxygen content, and are also able to recycle C, S, and N, essential elements for the ecosystem [111].

Soil microorganisms may be compromised by the excessive use of chemicals and presence of heavy metals, and long-term fertilization practices [104,112–114]. Many studies showed that soil tillage can adversely affect microbial activity in the rhizosphere. As reported by Holthusen et al. [115], improper soil management, increasing farm machinery mass, and traffic frequency threaten the ecological functionality of soils under intensive cropping systems. Kabiri et al. [116] highlighted that less disturbed soils present more microorganisms than soils cultivated with conventional methods. Therefore, conservative processing protects soil microorganisms. This type of conservation practice is part of the plan of "Land Restoration", as indicated by Sustainable Development Goal 15.

Promoting soil microorganism growth also means improving crop productivity. Indeed, some microorganisms are able to: produce auxins and gibberellins (arbuscular mycorrhizal fungi) [117]; have a bio-pesticide activity (*Bacillus*, *Trichoderma* and *Pseudomonas*) [118]; act as biofertilizers (*Rhizobium*, *Azotobacter*, *Azospirillum*) [119–121]; fix atmospheric N (*Azotobacter* and *Azospirillum*) [122]; and decompose organic waste (*Lactobacilli* and *Rhizobium*) [123]. Microorganisms can be stimulated through new techniques such as soil and seedling inoculation, transgenesis, and plant breeding. Soil and plant inoculation have been shown to positively influence crop productivity [124]. The introduction of beneficial microbes will change the rhizosphere microbiome by improving plant productivity and yield. Transgenesis can be useful in the development of stress resistance [125]. For example, the introduction of *Gluconacetobacter diazotrophicus* PAL5 in sugar cane led to the development of drought resistance according to Vargas et al. [126].

International commitments are needed to address inadequate land use practices, especially in the agricultural sector. Soil scientists, research organizations, policy makers, and governments must make workers in the sector aware of the damage being done to soil microbiome. A study conducted by Satti et al. [127] showed that the degradation of PLA in soil did not affect the nitrification activity of microorganisms. Instead, Ardisson et al. [128] studied a biodegradable plastic material based on corn starch and biodegradable copolymers in soil for 29 days. They found that compared to bioplastic-free control tests, the activity of microorganisms increased with the addition of biodegradable plastic. Fontanazza et al. [129] isolated the mesophilic bacterium *Pseudomonas putida* from soil particles attached to the surface of a BdPM. They also demonstrated the good ability of the microorganism to biodegrade the mulch. Another study examined how the soil extracts examined during the PHBV degradation process were not found to be toxic to *Vibrio fischeri* bacteria [130]. Biodegradable plastic mulches have been shown to interact with soil microbial communities both during their application and after their incorporation into the soil. For example, in two different soils, a PBAT-PLA mulch on a cotton crop for seven months not only increased the presence of soil bacteria, but also the distribution of specific species [131]. The changes were soil-dependent, where one of the soils had been enriched in bacterial groups.

Wang et al. [132] studied the effects of plastic film residues on the occurrence of soil phthalates (PAE) and microbial activities using a batch pot experiment. PAE concentrations increased with increasing plastic film residues, while for the soil microbial C and N, enzyme activities, and microbial diversity, a significant decrease was found. Soil microbial activity was positively correlated with soil PAE concentration, and soil PAE concentrations were impacted by plastic color and residue volume. Jeszeová et al. [133] investigated the change of the microbial community responsible for the biodegradation of different polymeric foils (one cellulose mat and 3 PLA/PHB blend films) after one year of incubation into respirometric reactors. Culture-dependent and culture-independent strategies were combined with different agar degradation assays in order to characterize the degrading microbiome. Both types of analysis showed how the microbiome changed on the basis of available substrate. The DGGE-cloning investigation increased the information about the microbial communities occurring during bioplastic degradation detecting several bacterial and fungal taxa, and some of them (members of the orders *Anaerolineales*, *Selenomonadales*, *Thelephorales*, and of the genera *Pseudogymnoascus* and *Pseudeurotium*) were revealed for the first time.

Finally, the results of several studies suggest that biodegradable mulching can change the soil and interaction with microbial communities, both fungal and bacterial, not only after burying into the soil, but also previously, when the bioplastic covers the soil surface around the crop. Biodegradable plastics and soil microbial communities can significantly interact right away after the film installation process in buried edges and at the bottom of the film surface mulching, which is in direct contact with the soil. The assessment of the impact of biodegradable plastic mulches and their degradative compounds on soil health and microorganisms must be studied from the beginning of bioplastic film application [134].

To discuss the effect of mulches on soil microbial populations, the papers by Bandopadhyay et al. [135] and Moore-Kucera et al. [136] were considered. In both papers, mulch treatments were studied in relation to two locations, one characterized by humid subtropical climate (Cfa, according to the Köppen classification) and silt loam soil (Humid/Si), and the other characterized by temperate oceanic climate (Cfb, according to the Köppen classification) and sandy loam soil (Ocean/Sa). In the Ocean/Sa location, the classes of bacteria found in the soil always exceeded those found in the Humid/Si location (Table 2), while the composition of the communities found on the mulches seemed to depend on both the mulches and the locations (Table 3). Finally, among the classes of bacteria associated with mulches, there are 5 that do not belong to those associated with soil (Tables 2 and 3). Among these, the most important was Deinococci, which was found in significant percentages on all the mulches and in both locations (Table 3). In Table 4, there is the comparison between the fungal populations of soils in close contact with two biodegradable mulches (starch-based and paper) compared with a control (no mulch). Among the identified fungi, those belonging to the Ascomycota division were prevalent, and within this, the Sordariomycetes class was the most considerable one (Table 4). The genera *Fusarium*, *Volutella*, and *Humicola* were greatly affected by the location, suggesting that, similarly to soil bacteria, soil fungi are affected by pedoclimatic conditions rather than by mulches. The fungi populations associated with mulches appear to be very different from those associated with soil. Observing Table 5, in fact, it emerges that the fungi belonging to the Basidiomycota division are present on mulch to a significantly higher extent than in the soil. In addition, the percentage of Basidiomycota is decidedly higher in Ocean/Sa than in Humid/Si (Table 5); from this, it can be deduced that even the composition of the fungal populations present on mulch strongly depends on the location. Observing the classes, Dothideomycetes stands out on all plastic films, both biodegradable and non-biodegradable. The Tremellomycetes class has the highest percentages among the Basidiomycota on plastic films (biodegradable or not), but only in the Ocean/Sa location. The fungal populations on paper mulch have peculiar characteristics, with high percentages of Agaricomycetes both in Humid/Si and in Ocean/Sa, and with a high percentage of Pezizomycetes, but only in Humid/Si.

Table 2. Populations of bacteria, expressed as percentages and divided by classes, found in the soil under different mulches and in two locations. Humid/Si: location with humid subtropical climate (Cfa, according to the Köppen classification) and silt loam soil. Ocean/Sa: location with temperate oceanic climate (Cfb, according to the Köppen classification) and sandy loam soil. Values below 1% were excluded. Adapted from Bandopadhyay et al. [135].

Classes	**PBAT and Starch**		**PET and Starch**		**PBAT and PLA**		**PLA and PHA**		**Paper**		**PE**	
	Humid/Si	**Ocean/Sa**	**Humid/Si**	**Ocean/Sa**	**Humid/Si**	**Ocean/Sa**	**Humid/Si**	**Ocean/Sa**	**Humid/Si**	**Ocean/Sa**	**Humid/Si**	**Ocean/Sa**
						%						
Acidobacteria Gp4	5	6	4	6	7	6	3	6	4	7	6	6
Acidobacteria Gp6		6		6		6		5		5		5
Acidobacteria Gp7	7	4	6	4	8	4	6	4	5	5	7	4
Acidobacteria Gp16	3	4	2	4	3	4	2	4	2	4	3	4
Actinobacteria	14	9	15	9	11	7	14	9	16	10	15	9
Alphaproteobacteria	9	9	9	9	8	9	10	10	11	10	7	10
Bacilli	4	2	5	2	4	2	4	3	4	2	4	2
Unclassified bacteria	29	29	28	31	30	30	29	29	28	27	31	29
Betaproteobacteria	4	4	4	5	4	4	4	5	4	5	3	5
Gammaproteobacteria		6		4		5		5		6		7
Planctomycetacia	8	5	9	5	8	5	9	6	8	5	8	5
Spartobacteria	3		3		3		2		4		2	
Number of classes	**10**	**11**	**10**	**11**	**10**	**11**	**10**	**11**	**10**	**11**	**10**	**11**

Table 3. Populations of bacteria, expressed as percentages and divided by classes, found on different mulches and in two locations. Humid/Si: location with humid subtropical climate (Cfa, according to the Köppen classification) and silt loam soil. Ocean/Sa: location with temperate oceanic climate (Cfb, according to the Köppen classification) and sandy loam soil. Values below 1% were excluded. Adapted from Bandopadhyay et al. [135].

Classes	PBAT and Starch		PET and Starch		PBAT and PLA		PLA and PHA		Paper		PE	
	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa
						%						
Acidobacteria Gp16									8			
Actinobacteria	22	24	27	28	28	30	29	31	14	29	20	25
Alphaproteobacteria	42	17	41	26	41	19	42	21	25	28	14	14
Armatimonadia										1		
Bacilli	3	2	2	2	5	5	6	4			35	5
Unclassified bacteria	3	1	14	1	5	3	3	5	29	5	8	8
Betaproteobacteria	18	19		16	9	14	7	10	3	8	5	13
Deinococci	2	15	7	11	2	10	5	15	8	4		4
Flavobacteria						1						
Gammaproteobacteria	3		3		2	4	1				9	
Planctomycetacia									3			
Sphingobacteria		16		10		10		7	2	16		15
Thermomicrobia	2				4		3		2			
Number of classes	**8**	**7**	**6**	**7**	**8**	**9**	**8**	**7**	**9**	**7**	**6**	**7**

Table 4. Populations of fungi, expressed as percentages and divided by taxa, found in the soil close contact with two biodegradable mulches and in two locations. Humid/Si: location with humid subtropical climate (Cfa, according to the Köppen classification) and silt loam soil. Ocean/Sa: location with temperate oceanic climate (Cfb, according to the Köppen classification) and sandy loam soil. Values below 1% were excluded. Adapted from Moore-Kucera et al. [136].

Division	Class	Order	Family	Genus	Starch-Based		Paper		No Mulch	
					Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa
							%			
Ascomycota	Dothideomycetes	Pleosporales	Didymellaceae	*Leptosphaerulina*					5	
			Leptosphaeriaceae	*Leptosphaeria*			13			
			Other		7		1		7	
	Eurotiomycetes	Onygenales	Onygenaceae	*Chrysosporium*		5		1		
	Leotiomycetes	Chaetomellales	Chaetomellaceae	*Chaetomella*	1					
		Helotiales spp					20			
	Sordariomycetes	Glomerellales	Plectosphaerellaceae	*Plectosphaerella*						2
		Hypocreales	Nectriaceae	*Fusarium*	37	3	27	2	20	3
				Volutella	12		1		3	
				Other	12	11	11	6	17	14
		Sordariales	Chaetomiaceae	*Humicola*	20		13		26	
			Lasiosphaeriaceae	Unidentified		7		1		3
		Other			2	5		1	2	3
	Other				3	4	8	6	4	1
	Unidentified					18		56		
Basidiomycota	Tremellomycetes	Tremellales	Cryptococcaceae	*Cryptococcus*		4	2	1	1	2
Other fungi					1	14	1	11	1	56
Unidentified					1	10	1	3	1	4

Table 5. Populations of fungi, expressed as percentages and divided by classes, found on different mulches and in two locations. Humid/Si: location with humid subtropical climate (Cfa, according to the Köppen classification) and silt loam soil. Ocean/Sa: location with temperate oceanic climate (Cfb, according to the Köppen classification) and sandy loam soil. Values below 1% were excluded. Adapted from Bandopadhyay et al. [135].

Division	Class	PBAT and Starch		PET And Starch		PBAT and PLA		PLA and PHA		Paper		PE	
		Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa	Humid/Si	Ocean/Sa
								%					
Ascomycota	Dothideomycetes	71	52	91	50	74	49	77	50	9	3	49	62
	Eurotiomycetes							1				2	3
	Leotiomycetes		1		1		3		2			6	
	Orbiliomycetes									5			
	Pezizomycetes									38			
	Sordariomycetes	13	2	7		14	2	16	6	4		37	10
	Unclassified									6			
Basidiomycota	Agaricomycetes	2				1				29	67		
	Cystobasidiomycetes	2	4										
	Microbotryomycetes	9	9	2	8	8	6	5	7		7		2
	Tremellomycetes		31		39	1	40		31		5		22
	Ustilaginomycetes	1	1			2		1	4				
Chytridiomycota	Incertae sedis									9	17		
Mucoromycota	Incertae sedis											6	
	Number of classes	**6**	**7**	**3**	**4**	**6**	**5**	**5**	**6**	**7**	**5**	**5**	**5**

6. Effect of BdPMs on Weed Control

Effects of BdPMs on weed control are not homogenous in the literature, since equal or below-average suppression levels than PE mulch are reported based on mulch type, climatic zone, and agronomic management (Table 6). In a two-year Mediterranean greenhouse study on organic tomato, Marín-Guirao et al. [137] concluded that the average percentages of weed presence showed no significant differences between PE mulch and BdPMs. Similar results were obtained by Minuto et al. [138] for vegetable crops in northern Italy, both in open field and under greenhouse. On the contrary, comparing a black PE mulch and four black BdPMs to growers' standard practice of bare ground cultivation in a floricane red raspberry (*Rubus idaeus* L.) production system in north-western USA, Zhang et al. [139] indicated that cumulative weed number and biomass were greater in the control than all mulched treatments, with PE mulch better performing than BdPMs. Factors affecting weed control efficacy of BdPMs are the climate, soil physio-chemical properties, key product ingredients, films color and thickness, and the biological characteristics of weeds present.

The geographical area where a mulching film is going to be used influences its duration, which is positively correlated to its weed-suppressive ability. Under semi-arid climates, for example, BdPMs generally have a shorter duration than in temperate zones, due to the high solar radiation intensity, humidity level, and soil temperature that stimulate the degradation processes [140]. For instance, in a three-year multi-location field experiment performed under semi-arid conditions in processing tomato, Cirujeda et al. [141] found that, averaged over locations and years, the tested BdPMs (black Mater-Bi©, black Biofilm© and black Enviroplast©) were capable of reducing weed biomass as much as PE.

The effectiveness of the BdPMs in containing weeds also depends on the biological characteristics of the latter (life span cycle, eco-physiological group, etc.). In fact, since they degrade quickly, BdPMs generally control annual seeded weeds better than perennials reproduced vegetatively (by rhizomes, tubers, etc.), which can persist in the soil for longer periods. Nevertheless, weeds requiring light to germinate such as *Avena fatua* L., *Echinochloa cruss-galli* (L.) P.Beauv., and *Lamium amplexicaule* L. are more susceptible to BdPMs than weeds that do not require light. It should be also considered that some BdPMs can be pierced by certain spiny weeds [e.g., *Cyperus rotundus* L., *Rumex hypogaeus* T.M.Schust. & Reveal, *Sonchus asper* (L.) Hill, *Cirsium vulgare* (Savi) Tenore, *Xanthium spinosum* L., etc.] and, thus, they are not recommended for their control. However, the type of BdPM material highly affects the capacity of weed control and can overcome this issue. In a meta-analysis performed by Tofanelli and Wortman [142], for example, it was found that paper-based mulches reduced weed pressure by ~88% compared to PE mulch, whereas starch-polyester and other bio-based films were less effective than PE mulches. In addition, the authors documented a strong efficacy of paper-based mulch in controlling sedge weeds (*Cyperus* spp.). Evaluating several BdPMs, paper mulches, and PE on purple nutsedge (*C. rotundus*) control in a four-year field experiment carried out in a semi-arid climate, Marí et al. [143] found that only paper-based mulches controlled this species effectively, as the leaves were unable to pierce the material. Cirujeda et al. [141] also reported a stronger reduction in purple nutsedge biomass by paper-based mulch than PE and starch-polyester mulches.

Another important aspect affecting the weed-suppressive ability of BdPMs is their color, since weed growth under plastics is strongly related to PAR transmission (400–700 nm) [144]. In general, black BdPMs are more effective than white ones in reducing the quantity and influencing the quality of light transmittance through the mulch. Indeed, studying the effect of several BdPMs and PE films with different colors on pie pumpkin in north-western USA under Mediterranean conditions, a low weed number and biomass was found among different BdPMs, except for a white BdPM (PLA + PBAT) and a clear PE mulch [145]. Similarly, in another study carried out in high tunnel tomato production, Cowan et al. [146] concluded that, except for white ones, black and brown BdPMs controlled weeds as much as black PE mulch. Comparing a black and a white PLA mulch to a conventional low-density PE mulch as control, a comparable weed control efficiency to the control was found only with the black PLA mulch. According to the authors, the poor performance of white PLA mulch could be attributable to its high light transmission, which increased soil temperature and created a microclimate conducive to weed germination.

Although the weed-suppressive ability of BdPMs is generally lower than PE plastic mulching, they show good level of weed control combined with other agronomic performances such as soil moisture conservation, regulation of soil temperature, enhancement of nutrient availability, etc. Moreover, BdPMs do not impact the environment and present a favorable economic return. In this regard, despite the more expansive base material, the high costs of removing and recycling PE mulching films make BdPMs a valid economical alternative, especially in Mediterranean conditions, where the costs do not account more than 0.2% [147].

Table 6. Weed-suppressive ability of different bio-plastic film mulches vs. polyethylene mulch.

References	Product Name	Thickness (µm)	Key Product Ingredient(s)	Effect on Weeds	Main Crop
Zhang et al. [139] *	black polyethylene	15.0	PE	97.2% WC	*Lycopersicon esculentum* (L.) Karsten ex Farw.
	black Mater-Bi®	15.0	Starch based, organic polyesters	91.5% WC	
	black Biofilm®	17.0	Organic polyesters + natural plasticizer	86.0% WC	
	black Enviroplast®	15.0	Oxo-degradable plastic mulch	94.3% WC	
Zhang et al. [145] *	black polyethylene	25.4	PE	0.1 weed m^{-2}	*Cucurbita pepo* L.
	clear polyethylene	25.4	PE	10.1 weed m^{-2}	
	clear Organix	17.8	PLA + PBAT	34.5 weed m^{-2}	
	black Organix	15.2	PLA + PBAT	2.3 weed m^{-2}	
	black film organic	15.2	–	0.3 weed m^{-2}	
	black AMX-01	254.0	not provided by manufacturer	0.4 weed m^{-2}	
	brown WeedGuardPlus	240.0	Cellulose	1.0 weed m^{-2}	
Marín-Guirao et al. [137] *	black polyethylene	37.5	PE	~20% WP	*L. esculentum*
	Sotrafilm NG Bio	18.0	PLA + PBAT	~18% WP	
Ngouajio et al. [144] *	low-density polyethylene	25.0	PE	100.0% WC	*L. esculentum*
	black Ecoflex®	25.0	PBAT	97.2% WC	
	white Ecoflex®	25.0	PBAT	28.74% WC	
	black Ecoflex®	35.0	PBAT	98.5% WC	
	white Ecoflex®	35.0	PBAT	33.7% WC	
Marí et al. [143] *	low-density polyethylene	15.0	PE	~66% NC	*Capsicum annuum* L.
	black Sphere® 4	15.0	Potato starch	~56% NC	
	black Mater-Bi®	15.0	Corn starch, co-polyester, vegetable oils	~63% NC	
	black Sphere® 6	15.0	Potato starch	~62% NC	
	black Bioflex®	15.0	PLA, co-polyester	~55% NC	
	black Ecovio®	15.0	PLA	~56% NC	
	light brown Arrosi® 240	80.0	Cellulosic fiber	~91% NC	
	light brown Arrosi® 69	80.0	Cellulosic fiber	~96% NC	
	black Mimgreen®	85.0	Cellulosic fiber	~99% NC	

* averaged over locations and/or years; PE: polyethylene; PLA: polylactic acid; PBAT: polybutylene adipate-co-terephthalate; WC: weed control; WP: weed presence; NC: nutsedge control.

7. Effect of Biodegradable Mulches on Soil Properties

Mulches affect many soil properties such as temperature, structure, moisture, water/air ratio, etc. The effect of mulches on the thermal regime depends on the material from which they are made, their transparency to solar radiation, and their thickness [22,148]. BdPMs increase soil temperature compared to bare soils [142]. In contrast, spray formulations do not appear to have obvious effects on soil temperature, as demonstrated by Fernández et al. [149] with a hydrophobic formulation based on a polysiloxane polymer. Ramakrishna et al. [150] reached the same conclusion using a sprayable hydrophilic polymer on a groundnut crop. Figure 8 was constructed using data from Ramakrishna et al. [150], who compared a PE conventional plastic mulch (CPM), straw mulch (SM), a hydrophilic sprayable mulch (HSM), and no mulch (NM). In the experiment, the measurements were made at 3, 30, 60, and 90 days after sowing and at three times, i.e., at 6 AM, at noon, and at 6 PM. However, in Figure 8, only the mulch effect is considered. Confidence intervals were constructed from standard deviations and the number of measurements. The means were separated with the Z test:

$$Z = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{\sigma_1^2}{n_1} + \frac{\sigma_2^2}{n_2}}} \quad (1)$$

where $\overline{x}_1$ and $\overline{x}_2$ are the means of two different treatments; σ_1^2 and σ_2^2 are the variances of two different treatments; n_1 and n_2 are the number of samples of two different treatments.

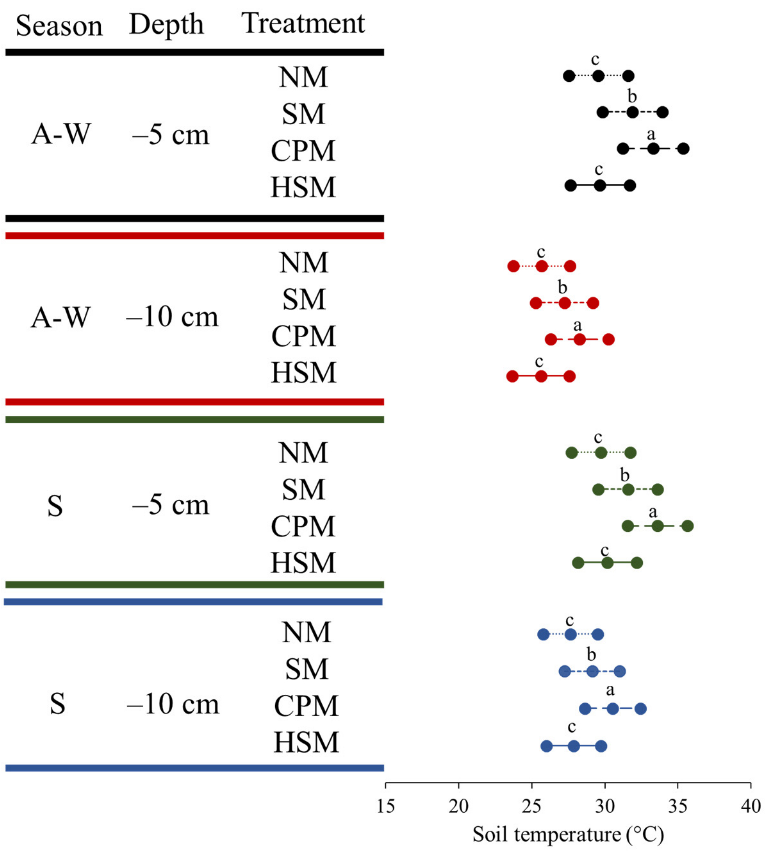


Figure 8. Average soil temperatures and relative 95% confidence intervals obtained in response to the different mulching treatments in the experiment by Ramakrishna et al. [150]. The values were grouped by season and measurement depth. Different letters within each season/depth indicate significant differences between treatments ($p \leq 0.05$). A–W: autumn-winter cycle; S: spring cycle; NM: no mulch; SM: straw mulch; CPM: conventional plastic mulch; HSM: hydrophilic sprayable mulch.

Figure 8 shows patterns that are repeated constantly, regardless of the season and depth of measurement. In fact, the temperature under the CPM is always significantly higher than that under the SM (Figure 8). The latter is always significantly higher than that obtained with the treatment with HSM, and that obtained without mulching (NM) (Figure 8). Finally, HSM and NM never showed statistically significant differences (Figure 8). During the autumn-winter season, the average soil temperature under the CPM treatment was 11.7% higher than that of the HSM treatment at depth of −5 cm, and 9.7% higher at depth of −10 cm (Figure 8). During the spring season, the average soil temperature under the CPM treatment was 10.8% higher than that of the HSM treatment at depth of −5 cm, and 9.6% higher at depth of −10 cm (Figure 8). Rain can cause the breakdown of structural aggregates, partly due to the alternation between drying and wetting, and partly due to the kinetic energy of the drops [151]. Soil mulching can preserve soil aggregates from the action of the rain, both by protecting soil surface from air-drying and quick submergence in water, and by protecting it from the impact of drops [152]. Domagała-Świątkiewicz and Siwek [153], comparing bare soil treatment with two nonwoven BdPMs (made of PBS) treatments in an onion crop, found that the latter increased the percentage of soil large stable aggregates (2.5 mm < Ø < 4.0 mm) and decreased that of aggregates with dimensions between 0.25 and 1.0 mm. This change in soil structure is accompanied by a decrease in bulk density, with a consequent decrease in soil compaction [154]. Both of these effects are associated with an increase in pore size and soil aeration [155]. Improving the soil structure can result in an increase in the water retention capacity [153,154], and this is just one of the reasons why mulching can have a positive effect on the water content of the soil. Changes in soil moisture in the surface layer (0–10 cm) may vary dynamically due to water vapor flows through the soil-atmosphere interface [156], but the humidity-temperature fluctuation in the soil can be reduced with mulching [31]. The latter can also be seen as a technique that allows saving irrigation water, because it conserves soil water by reducing evaporation. This fact is of utmost importance, especially in drylands [157]. Furthermore, mulching can improve the water infiltration rate, which may be defined as the meters per unit time of water entering the soil [158], by reducing the compaction caused by the impact of raindrops [159]. The effect of mulching on water infiltration rate is one of the aspects studied by Sintim et al. [160], who conducted a four-year test on the same soil. They compared two BdPMs, namely BioAgri, a commercial product with starch, and PBAT, and a PLA/PHA blend film, an experimental product composed of 86% PLA and 14% PHA. Together with BdPMs, a paper mulch and a CPM made of PE were also compared. Figure 9 shows 95% confidence intervals of the water infiltration rate values corresponding to the different treatments in the different years. Confidence intervals were constructed from standard deviations and the number of measurements. What stands out when looking at the graph is that, except for the first year, the water infiltration rate values resulting from the mulch treatments are significantly higher than the one resulting from no mulch treatment (Figure 9). Another interesting fact is that treatments with BdPMs have given results comparable to those of CPM. Soil texture values, together with soil hydraulic parameters of the experiment conducted by Chen et al. [161] were used in the formulas collected by Saxton and Rawls [162] to construct the water retention curve in Figure 10. This curve indicates the water content values of the first 20 cm of soil corresponding to the three treatments under study, namely: soil covered with CPM made of PE, soil covered with BdPM, mostly made of polysaccharides such as cellulose and starch, and no mulch (NM). The graph shows that the average moisture content of the soil in terms of volume during the test period was quite similar in BdPM and CPM (19.3% vs. 23.8%, respectively), while the moisture content of NM was significantly lower than the first two (11.0%). Furthermore, the soil porosity of the experiment of Chen et al. [161] is about 42%. This means that the BdPM average soil moisture value of 19.3% is the 46% of the total porosity. This percentage is very close to 50%, which is considered ideal for both the roots of cultivated plants and for microbial growth [163]. As expected, the estimated mean matric potential of soil treated with BdPM (−83.5 kPa) was slightly lower than that of soil treated with CPM (−56.8 kPa), but was significantly higher than that estimated for the NM treatment (−234 kPa) (Figure 10). Regarding the water/air ratio, in theory, the more air there is in the soil, the better. However, plants also need water and where there is water there can be no air. In other words: water drives the air out of the soil. An air defect affects the respiration of the roots, leading to an excess of carbon dioxide in the soil and compromising all the processes that take place thanks to oxygen. A content of 5% of carbon dioxide in the soil air is the limit above which breathing becomes difficult, the same is true when the oxygen content falls below 10% [164]. The amount of air that a soil can contain depends on its porosity and the amount of water contained in the pores. The size variability of pores (micro- and macropores) in the soil results in the coexistence of unsaturated and water-saturated pores close to each other. For soil microorganisms this variability is very important. In fact, bacteria and protozoa are essentially aquatic and live in thin water-films on the surfaces of the pores. Other organisms, such as fungi, benefit from both the presence of water and the presence of air in the macropores [165]. Therefore, the ability of the soil to retain and drain water is a key feature of the soil ecosystem and, for this reason, it is important to study the relationship between the soil water content and the matric potential.

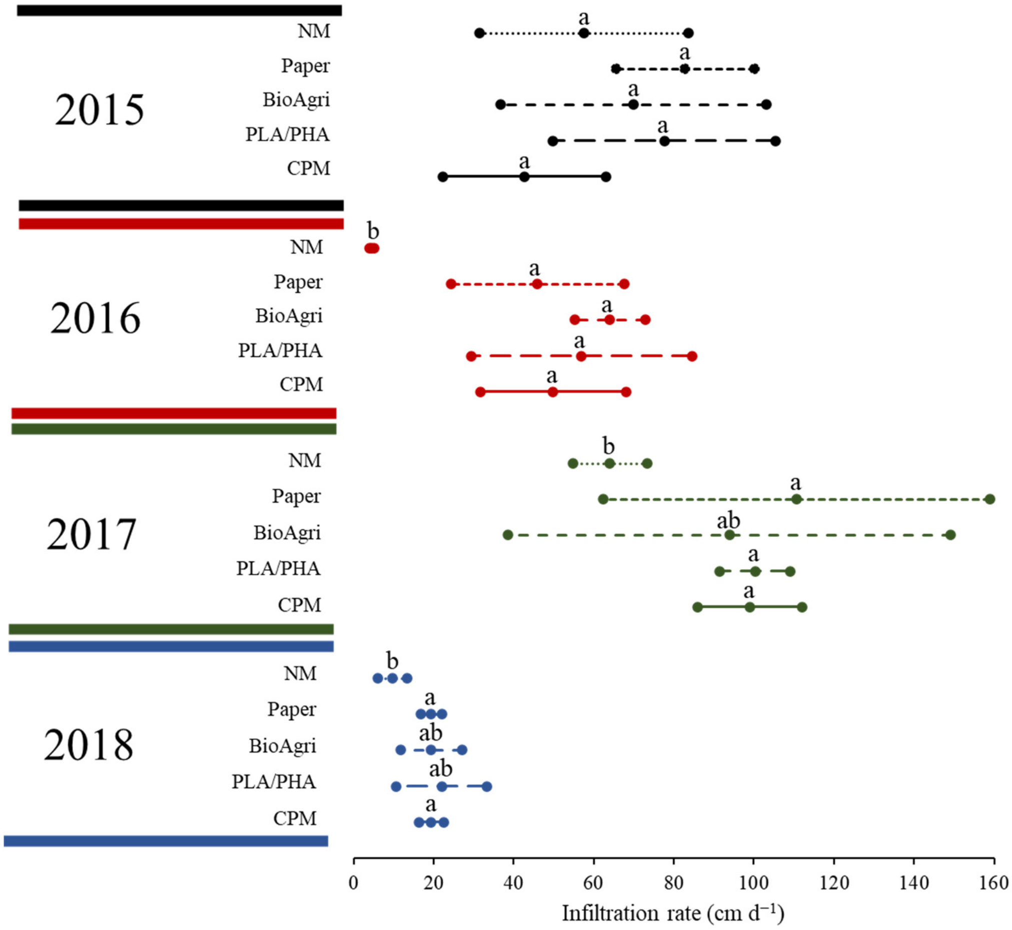


Figure 9. Average soil water infiltration rates (and relative 95% confidence intervals) obtained in response to the different mulching treatments in the experiment by Sintim et al. [160]. The values were grouped by year. Different letters within each year indicate significant differences between treatments ($p \leq 0.05$). BioAgri: biodegradable film composed by starch and PBAT; NM: no mulch; PLA/PHA: biodegradable film composed by PLA and PHA; CPM: conventional plastic mulch (PE); paper: cellulosic-paper mulch.

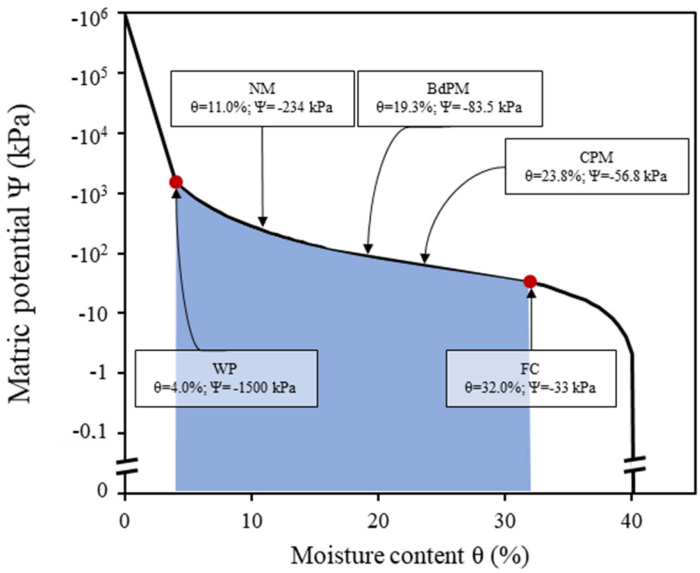


Figure 10. Water retention curve of the soil described in Chen et al. [161]. The values of the matric potential were expressed in the vertical axis in a base 10 logarithmic scale. To construct the curves, the equations collected in Saxton and Rawls [163] were used. The blue colored area represents the plants' available water, between matric potential values of −33 kPa (field capacity) and −1500 kPa (wilting point). BdPM: biodegradable plastic mulch; FC: field capacity; NM: no mulch; CPM: conventional plastic mulch.

8. Conclusive Remarks

Mulching is a widespread adopted technique in several cropping systems. Its effectiveness in improving physical, chemical, and biological soil properties, as well as in containing weeds, is an established fact. Mulching can be made using various materials, with conventional plastics (i.e., of fossil origin and non-biodegradable) currently by far the most used. However, the fate of mulching plastic films at the end of their use represents a serious concern, since their recycling is not always easy and their residues fragment until becoming "microplastics", which are a threat to the environment. Another serious problem linked to conventional plastics is their fossil origin. For these reasons, in recent times, the use of BPs, i.e., plastics of biological origin and/or biodegradable, is slowly spreading, also for mulching. In particular, BdPMs provide several benefits in the production of vegetables and other specialty crops, such as the increase in agroecosystem sustainability by controlling weeds and limiting the use of agrochemicals; the maintenance of physical characteristics and moisture of soil reducing tillage and irrigation supplies, respectively; and the increase in biodiversity improving the habitat for microbial communities in terms of water/air ratio and thermal state of soil.

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