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## **Biodegradable Mulch for Vegetable Production. A Review**

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### **ABSTRACT**

From a crop production perspective, plastic mulches can increase yields. The use of plastic mulch in agriculture has increased dramatically in the last 10 years throughout the world. This increase is due to benefits such as increase in soil temperature, reduced weed pressure, moisture conservation, reduction of certain insect pests, higher crop yields, and more efficient use of soil nutrients. Also mulching with plastic mulch is used commonly on large scale it remains 15% - 20% moisture conservation because, mulching with plastic materials that cover the soil creates a physical barrier to soil water evaporation. Plastic pollution in agricultural soils, caused by the incomplete removal of polyethylene mulch after usage, is a growing environmental concern. Where, Current polyethylene plastic mulch film is not biodegradable and therefore cannot be plowed back into the soil. This causes irreparable harm to ecosystems and the habitats. However, disposing of used plastic films, which cause pollution, has led to development of photodegradable and biodegradable mulches (BDMs). There has therefore been increased interest in biodegradable plastic mulches as alternative to polyethylene mulch; completely soil-biodegradable plastics or compostable plastics offer an environmentally responsible end-of-life solution for plastic mulch film and plasticulture products. Using alternative biodegradable materials as covers has been of increasing interest in recent years. However, little is known about their impact on soil health. Here we review the use of plastic mulches in agriculture, with special reference to biodegradable mulches.

**Keywords:** Plasticulture, Plastic mulch, Polymers, Plastic pollution, Biodegradable mulch, Biodegradation

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### **1. Introduction**

Farmers and horticulturists use mulching as a method of improving the condition of agricultural soils by covering the soil surface with different kinds of materials Bot and (Kasirajan and Ngouajio 2012; Bastioli 2014). Benefits of mulching on growth and yield of annual and perennial crops have long been recognized (Shen *et al.*, 2020; Serrano-Ruiz *et al.*, 2021). Mulching with organic or inorganic materials aims to cover soils and form a physical barrier to limit soil water evaporation, control weeds, maintain a good soil structure, and protect crops from soil contamination. Natural mulches are those derived from animal and plant materials. If properly used, they can offer all the benefits of other types of mulches. Natural mulches help in maintaining soil organic matter and tilth (Sanchez *et al.*, 2008). And provide food and shelter for earthworms and other desirable soil biota (Romen *et al.*, 2004).

A few years ago, mulch film was the second most important application of plastics in agriculture after plasticgreen houses or tunnels (Espinoza *et al.*, 2006), and by 2012, global use of plastic for agriculture was about 2.8 million tones. Mulch is now the largest use of plastics in agriculture and the market is hugely growing especially in China, where more than half of the globally applied plastic mulch is used. Although the largest demand of plastics is in Asia, demand is expected to grow strongly in Latin America, North America, the Levant and the Middle East (Reynolds, 2010).

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With the advent of polyethylene, Plasticulture, a term refers to the use of plastic materials in agriculture (mainly mulch, low tunnel, green houses cover, polarization film, fumigation film, and packaging), burst Kumar *et al.*, (2020). Polyethylene is widely used as a mulch in agriculture and horticulture (Espinoza *et al.*, 2006), and black-colored film has been the most popular in production (Mooney 2009).

From a crop production perspective, plastic mulches can increase yields, extend the growing season, reduce weed pressure, increase fertilizer use efficiency, conserve soil moisture, and increase soil temperature (Lalitha *et al.*, 2010; Qi *et al.*, 2020). For these reasons, polyethylene mulches have been used in agriculture for over half a century (Lamont, 2005). So Plastic film used as mulch has revolutionized the age-old technique of mulching (Kasirajan and Ngouajio 2012). Of these mulches, only those made of polyethylene are still widely used today in the agricultural industry. (Fig. 1).



**Fig. 1:** Fresh market pepper production using raised beds covered with polyethylene mulch (Kader *et al.*, 2017).

A major limitation of polyethylene mulch involves disposal of mulch material following use. Current disposal options as reviewed by Hayes *et al.*, (2019) and Barragan *et al.*, (2003) include burning, incineration, recycling, composting and using landfills; each have major economic or environmental disadvantages (Kyrikou and Briassoulis, 2007; Lamont, 2005).

Alternative solutions for the use of plastics have been developed. From early 1980s, one alternative product has been biodegradable plastic (Zhang *et al.*, 2019). The raw materials have mainly been aliphatic polyesters and starchpolymer blends that are made from renewable non-oil resources (Halley *et al.*, 2001, Sanchez *et al.*, 2008). These innovations present an environmentally friendly solution to the increasing problem of plastic disposal (Serrano-Ruiz *et al.*, 2020). Biodegradable mulch films decompose slowly under moist soil, so they can be tilled into the soil after the growing period. Otherwise, biodegradable mulch films resemble PE-mulch films, as they can be laid on the soil in a similar manner and with the same equipment as PE-mulch films (Sanchez-Hernandez *et al.*, 2020). Martin-Closas *et al.*, (2017) have shown that the type of biodegradable plastic mulch they tested in Spain with organic tomato (*Lycopersicon esculentum* Mill.) production is a good alternative to black plastic.

## 2- History of plastic mulch

The practice of mulching as soil coverage with various materials to prevent the growth of weeds is very old. Since the ancient times (2500–3000 years Before Christ), people from several countries (Egyptians, Etruscans, Persians, Romans) adopted the mulching technique. They just simulated the leaves and woody debris sediments on the soil, which prevent the weed growth because of the combined effect of the solar radiation block and the biochemical action of the decomposition of organic materials.

We did not invent mulch. Mother Nature did. Before the use of plastic films, many different materials were employed for mulching: straw, dried leaves, bark of trees, cardboard, gravel, lapilli, jute, cocoa husks, natural fibers (mainly coconut and hemp) and organic waste (Serrano-Ruiz *et al.*, 2021).

While mulching with organic matter was already used in ancient agriculture, there is also a long history of lithic (stone) mulches. More than a thousand years ago, in both the Old and New Worlds, farmers used lithic materials to mulch their dry land fields to avoid drought and to improve crop yield. Stones, gravel, pebbles, volcanic ash and cinder as well as other lithic materials have been used. The method not only reduces evaporation but also decreases wind erosion and surface runoff from fields (Lightfoot 1996.).

In modern crop production several materials may be used for mulching. Farmers and horticulturists may choose among crop residues, different kinds of plastics, biodegradable films or different kinds of paper mulches coated or non-coated with plastic or biodegradable films. The effects of mulch type on crop growth can vary due to different production practices, growing conditions, and crop species (Kapanen *et al.*, 2008; Bandopadhyay *et al.*, 2018)

Crop residue mulching is a technique where the soil surface is covered by the organic residue of the previous crop (Erenstein 2002), such as straw, maize stalks, palm fronds or stubble of leafy organic material that may also be brought from elsewhere (Bot and Benites 2005). Organic mulches include woody materials such as bark or sawdust, and also compost that is increasingly available where municipalities have recycling systems for green waste (Merfield 2002).

Although the history of mulching with organic materials has been very long and beneficial for plant production, plastic mulches have widely replaced them and are very common practice, e.g., in vegetable production (Jenni *et al.*, 2004, Moreno and Moreno 2008). The use of plastics has dramatically increased and is still growing, especially in China where it is estimated that the annual use of plastics for mulching is some 700000 t (Espí *et al.*, 2006; Souza *et al.*, 2020). This review surveys the research on paper mulches and assesses the possibility for the use of paper materials to solve the problems of the immense use of plastics in agriculture and its environmental impact. In addition, we have reviewed the research conducted on several other mulch materials, in order to be able to compare the advantages and disadvantages of different mulch materials and to assess their potential in replacing plastic. An ideal mulch would be made of renewable material, biodegradable, durable, permeable to rain and irrigation water, suppress weed growth, and have a beneficial effect on soil temperature and moisture. Furthermore, it should be cost-effective and easily manageable, including laying it in the field.

### **3. Polyethylene plastic films for agricultural mulching:**

#### **3.1. General uses of plastic mulches:**

The use of plastic films for mulching, a technique that consists of covering the soil to improve microclimate for crop growth, has led to a revolution by increasing yield and allowing cultivation on lands where water and environmental conditions are limiting (Lamont, 2005; Kasirajan and Ngouajio, 2012; Kader *et al.*, 2017; Gao *et al.*, 2019). So, Plastic mulches alter the crop microclimate by changing the soil energy balance and modification of the crop microclimate results in changes in soil temperature that may affect plant growth and yield (Tarara 2000). Plastic mulch was first noted for its ability to increase soil temperature (Lambert *et al.*, 2017). The traditional black films used for mulching guarantee the mulching effect, thanks to the blocking of solar radiation because the filtering of Photosynthetically Active Radiation prevent weed growth (Ghimire *et al.*, 2020). The use of clear plastic mulch in cold areas or seasons increases soil temperature and promotes germination and emergence of many crops where soil temperature can be altered in regions of substantially high or low temperatures to encourage faster plant development (Miles *et al.*, 2017).

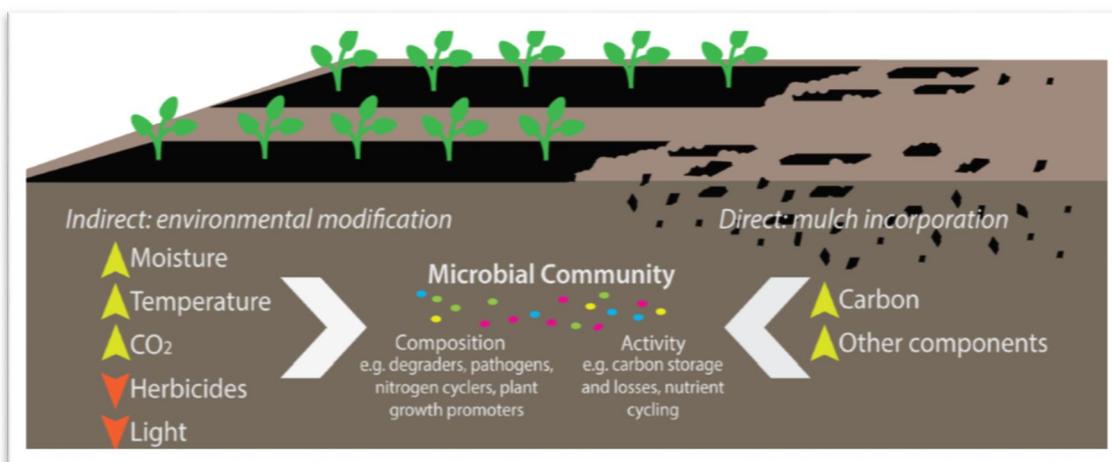
Most plastic mulches are made of low-density polyethylene (LDPE), a low cost and easy processing material fulfilling optical and physical properties mulches require: high puncture resistance, mechanical stretch, long durability and water impermeability (Espí *et al.*, 2006). Reported to be used from the 60's, global consumption of LDPE mulches continues to grow worldwide, with an increase of 35% between 2006 and 2017, up to over 2 Mt (Espí *et al.*, 2006; Le Moine and Ferry 2019). Asia Pacific, the main consumer, is expected to drive the global market in the forthcoming years (Transparency Market Research, 2013; Le Moine and Ferry 2019). Only in China, a 5-fold increase in plastic mulch consumption between 1991 and 2014 has been reported (Wenqing *et al.*, 2017).

The films can be colorless or pigmented, aluminized or white. The width is usually up to 3 m, thickness between 12 and 80  $\mu\text{m}$ , and they are often made of low density polyethylene. The planned lifetime of mulch films is usually two to four months (Espí *et al.*, 2006). Black polyethylene is the most widely used due to its excellent properties (Moreno and Moreno 2008). Polyethylene is light weight, inexpensive, durable and easy to handle.

Plastic mulches retain humidity and heat, prevent soil erosion and weed development. They favor plant development and fruitfulness and quality while decreasing water demand and herbicide and fertilizer requirements, a valuable contribution to sustainable agriculture (Kasirajan and Ngouajio, 2012).

Mulching reduces unproductive evaporation from the soil surface, so more water is available for transpiration, which is of benefit in water-limited conditions and plant water status is maintained (Cuello *et al.*, 2015). Organic mulch also reduces erosion by protecting the soil surface (Erenstein 2002) and reduces nutrient loss by runoff and leaching (Goldberger *et al.*, 2013).

Several field studies from semiarid northwestern China have shown that the use of plastic mulch can increase water use efficiencies and yields (Bu *et al.* 2013; Gao *et al.*, 2014). Li *et al.*, (2013) found that plastic mulch in a corn cropping system resulted in significantly higher soil water content as compared to no mulch, and water use efficiency of the corn crop increased by about 10 %. Similar results were reported from other studies in the same region (Zhao *et al.*, 2014; Gao *et al.* 2014; Qi *et al.* 2016). Increased soil water content under plastic mulch also has been reported from other regions in the world, including Nigeria (Anikwe *et al.* 2007), Pakistan (Chaudhry *et al.* 2004) India (Kumar and Dey 2011) Poland (Domagala Swiatkiewicz and Siwek 2013), and the United States (Wortman *et al.* 2015). Liu *et al.* (2013) reported that plastic mulch reduced soil water evaporation by about 90%.



**Fig. 2:** Indirect and direct effects of plastic mulching on soil ecosystems. Plastic mulches form a barrier on the soil surface which influences soil temperature, moisture and soil-air gas exchange, indirectly altering the microbial communities. BDMs are tilled into the soil at the end of the growing season, introducing physical fragments and a carbon source, along with other components of the plastic films (additives, plasticizers, minerals, etc.) which may additionally influence soil communities and their processes (Serrano-Ruiz *et al.*, 2021).

### 3.2. Plastic mulch and pest management

Reflected energy not only affects plant growth and development but reportedly influences the behavior of insects surrounding the plants (Hayes *et al.*, 2012; Kasirajan and Ngouajio 2012). Mulches may also protect the crop from insect pests or diseases, Reflective plastic mulch can be used to manage silver leaf whitefly populations equal to that provided by treatment with imidacloprid (Summers and Stapleton 2002). Since many insects use visual cues to find host plants, interference with these cues can cause increased attraction or repulsion to the plastic mulched fields and, thus, crops contained within those fields (Espí *et al.*, 2006). Greater numbers of western flower thrips (*Frankliniella occidentalis*) are attracted to low UV reflective white, blue, and yellow colors (Kasirajan and Ngouajio, 2012). Lower thrips counts were reported on red, green, black, and highly UV reflective substrates and aphids also

demonstrate attraction to certain colors, like yellow, green, and bare soil, and repulsion to other colors, such as silver (Lamont 2005).

In recent years, there has been increased attention to the use of colored plastic mulches in preventing or delaying the onset of various insect-vector diseases. The use of reflective mulch greatly reduced the number of aphid vectors and delayed the spread of bean yellow mosaic virus and cucumber mosaic virus (Jiang *et al.*, 2017; Kirstein *et al.*, 2019).

Ultimately improving crop productivity. Low-density polyethylene (PE) is the most commonly used plastic mulch because it is inexpensive, easily processed, highly durable and flexible (Kasirajan and Ngouajio, 2012). However, widespread use of PE, which is not biodegradable, has resulted in serious environmental contamination (Teuten *et al.*, 2009; Liu *et al.*, 2014; He *et al.*, 2015; Steinmetz *et al.*, 2016).

### 3.3. The effects of plastic mulch color

Most plastic products used in agriculture are either colorless or black. Some unique products may have chromatic colors. Different types and colors of plastic mulch have characteristic optical properties that change the levels of light radiation reaching the soil, causing increases or decreases in the soil temperature. Black and clear mulches have shown the greatest soil warming potential among the various mulch colors (Hussain and Hamid 2003).

Three basic mulch types have been used in commercial production: black, clear, and white-on-black plastic. Plastic mulches directly impact the microclimate around the plant by modifying the radiation budget (absorptivity vs. reflectivity) of the surface and decreasing the soil water loss. The color of mulch largely determines its energy-radiating behavior and its influence on the microclimate around a vegetable plant (Garry *et al.*, 2010; Gao *et al.*, 2019). Color affects the surface temperature of the mulch and the underlying soil temperature. The degree of contact between the mulch and soil, often quantified as a thermal contact resistance, can affect greatly the performance of a mulch. If an air space is created between the plastic mulch and the soil by a rough soil surface, soil warming can be less effective than would be expected from a particular mulch (Bastioli 2014). The change in vegetable crop yield in response to the different mulch colors is due in part to an increase in soil temperature and the range of reflected wavelengths produced by individual mulch colors (Jiang *et al.*, 2017; Kirstein *et al.*, 2019).

The soil temperature under a plastic mulch depends on the thermal properties (reflectivity, absorptivity, or transmittance) of a particular material in relation to incoming solar radiation. Black plastic mulch, the predominate color used in vegetable production, is an opaque blackbody absorber and radiator. Black mulch absorbs most UV, visible, and infrared wavelengths of incoming solar radiation and re-radiates absorbed energy in the form of thermal radiation or long-wavelength infrared radiation. Much of the solar energy absorbed by black plastic mulch is lost to the atmosphere through radiation and forced convection. The efficiency with which black mulch increases soil temperature can be improved by optimizing conditions for transferring heat from the mulch to the soil. Because thermal conductivity of the soil is high, relative to that of air, much of the energy absorbed by black plastic can be transferred to the soil by conduction if contact is good between the plastic mulch and the soil surface. Soil temperatures under black plastic mulch during the daytime are generally 5o F higher at a 2-inch depth and 3o F higher at a 4-inch depth compared to those that of bare soil (Brodhagen *et al.*, 2015; Miles *et al.*, 2017; Ahmed *et al.*, 2018; Serrano-Ruiz *et al.*, 2021).

The short-wave reflection, long-wave radiation, total radiant energy and latent heat flux that significantly control soil hydro-thermal characteristics are influenced by the colour of the plastic film (Filipović *et al.*, 2016)

Natural soils and plant residues (including mulches) are of many colors, and they can reflect a wide range of photosynthetic and morphogenic light to influence yield and quality of growing plants. Photosynthetically active light is a well-known component of the growth environment, contributing to more than 90% of the dry matter through photosynthetic process (Orzolek 2017). The most influential colors of morphogenic light appear to be far-red (FR), red (R), and blue (BL) (Andrady and Neal 2009).

Newer colors that are currently being investigated are red, yellow, blue, gray, and orange, which have distinct optical characteristics and thus reflect different radiation patterns into the canopy of a crop, thereby affecting plant growth and development (Ahmed *et al.*, 2018; Bandopadhyay *et al.*, 2018; Serrano-Ruiz *et al.*, 2021).

Red mulches were the first really new color to be investigated, other than the ones mentioned above and have started to be used commercially (Kim *et al.*, 2008). Li *et al.*, (2015) carried out a lot of trials on tomatoes, some that have shown a benefit of either improved yields or enhanced ripening and quality of the fruit. In other trials, there has not been a response. There is also some indication from different trials that red mulch may also be reducing the severity of early blight on tomatoes. This is indeed an interesting finding that may have some real benefit (Lamont 2005).

The following is a summary of several researches conducted on crop response to red, brown, green IRT, black, silver, white, blue (light and dark) and yellow color mulch is presented below:

Red plastic mulch has also been shown to increase yields in zucchini and in honeydews and muskmelons (Boots Kim *et al.*, 2008). Coventry *et al.*, (2003) found that colored reflective mulch (red mulch) increased soluble solids content, total phenolics (aromatic compounds which serve as anti-microbial protection), flavanols, and anthocyanins (water-soluble pigments related to flavonoids properties) content in Ontario wine grapes. Reflective mulch was also found to increase soluble solids in plums. Kasperbauer and Loughrin (2004) showed that altering the color of plastic mulch could alter anthocyanins content in butterbean. Strawberries that ripened over red plastic mulch were significantly higher in aroma and flavor compounds (Loughrin and Kasperbauer 2002). Antonious and Kasperbauer (2002) found that the use of yellow and black mulches resulted in higher concentrations of phenolics in carrot. Also, the use of yellow and white mulches resulted in higher  $\beta$ -carotene (organic compounds with orange pigments in plants) and ascorbic acid (water soluble sugar acid with antioxidant properties) content in carrots when compared to other colored mulches and bare soil treatments.



**Fig. 3:** The color of the mulch will influence the soil temperature, the surface temperature of the mulch and the light reflected by into the plant canopy, this can cause a difference in the impact a mulch can have on the soil and plant microenvironment. The last consideration is the difference in color retention, film appearance, and film longevity of mulches currently on the market. This is the critical question of what really is a red, blue or yellow mulch and how best do we define it (Garry *et al.*, 2010; kader *et al.*, 2020).

Also, Plants have shown a multitude of different responses when treated with blue (wavelength 400 to 500 nm) light. Blue light treatments have shown to affect morphological, metabolic, and directional reactions in plants (Garry *et al.*, 2010). Some of the documented findings on plant response to blue light include: phototropism (Boots *et al.*, 2019), enzyme synthesis (Briassoulis *et al.*, 2013), chloroplast development in leaves and stomatal opening (Garry *et al.*, 2010). Kasperbauer and Loughrin (2004) have found white plastic mulch to reflect more blue light than the other colored mulches used in their experiments.

#### **4. Plastic mulches: a source of pollution in agro ecosystems and for the environment:**

Many mulch films are currently produced from petroleum based plastics, usually polyethylene, and cause a considerable waste disposal problem (De Souza Machado *et al.*, 2018). Although the increasing use of plastic mulches has improved crop yields, it also has distinct drawbacks. However, Massive use of non-degradable LDPE mulches, valued for their high stability, is contributing to aggravating the generation and accumulation of high amounts of plastic wastes, an environmental concern for the agricultural ecosystem, has resulted in serious environmental contamination (Esmaeili *et al.*, 2013; Kasirajan and Ngouajio, 2012; Rodrigues *et al.*, 2019; Peng *et al.*, 2020). A major problem is how to remove the polyethylene from the field and how completely it can be done (Serrano-Ruiz *et al.*, 2021).

Plastic pollution in agricultural soils is an emerging environmental concern, requiring both science-based and strong policy interventions to alleviate the problem (Brodhagen *et al.*, 2017; De Souza Machado *et al.*, 2018).

Shogren and David (2008) estimated the cost of removal and disposal of plastic mulch from the field at 250 \$ ha<sup>-1</sup> in 2004. It seems to be even more laborious to remove the polyethylene that has been used to coat paper mulch when the paper part of the mulch has degraded (Miles *et al.*, 2005). Estimations account for 80% of all plastic waste ever generated to be presently accumulated in natural ecosystems or in landfills (Geyer *et al.*, 2017). Plastic fragments and compounds released from plastic wastes are ubiquitous all over the world, and can be found in the atmosphere, in water resources, as well as into soils and organisms, including humans (Schwabl *et al.*, 2019, Wong *et al.*, 2020).

Perhaps a major limitation to commercial uses of plastic mulches is the disposal of the plastic film after use, which causes an environmental pollution problem. The dramatic increase in production and lack of biodegradability of commercial polymers, particularly commodity plastics used in agriculture and packaging industry, focused public attention on a potentially huge environmental accumulation and pollution problem that could persist for centuries (Horton *et al.*, 2017; Wong *et al.*, 2020). Once plastics are buried, low temperatures and nutrient and oxygen availability slow down the (bio) degradation rate. As a result, persistence of the plastic fragments in soil environment is considerably greater than initially expected (Corcoran *et al.*, 2015; Li *et al.*, 2016). Material that is not recycled or properly disposed of can fragment, and cause environmental degradation of land and water resources. For example, crop yields were decreased when residual plastic film left in the soil was 58.5 kg ha<sup>-1</sup>. Recycling rates for mulches are substantially lower than the already low global plastic recycling rate, estimated below 30%. Mulches aggravate the plastic pollution mainly due to (1) the inability to recover all mulch fragments from the soil after use, releasing them and their plastic components to the agricultural soil, and (2) mismanagement of plastic mulch removal and low value of recovered mulch fragments. Plastics remaining at the end of the crop are to be collected and to enter an established waste management system. They can be recycled, used for energy recovery or accumulated in landfills. However, the recycling of agricultural plastic films faces specific difficulties. The cleaning steps required to eliminate soil, plants and agrochemicals adsorbed by the films increase complexity and are costly, and the agrochemicals they may release are harmful to the environment. High quantities of organic chemicals from fertilizers, pesticides and herbicides are traced in soils where plastic mulches have been used (Wong *et al.*, 2020). All these burdens lead to substantial mismanagement of the used mulches, being thrown to non-controlled environments, ending up in natural ecosystems or being burnt under uncontrolled conditions, releasing organic pollutants into the atmosphere (Zhang *et al.*, 2020; Hu *et al.*, 2020).

Another huge problem is disposal of the collected material, since it is non-biodegradable. The residues can contaminate the soil and pollute the environment, they may be put into landfills or buried in soil, and these methods are merely temporary rather than permanent solutions (Geyer *et al.*, 2017). If the mulches are burnt, it must be done at very high temperatures to avoid releasing toxic compounds such as Carbon and chloride oxides, this obviously is not happening in most cases. There is increasing evidence that plastic mulches may also increase level of phthalic acid esters (PAEs) in agricultural soil with a possibility of contaminating it, (PAEs) are hazardous to the environment and for human health (Horton *et al.*, 2017; Schwabl *et al.*, 2019). PAEs are able to migrate from plastic mulches to the soil and then to plants. High levels of PAEs have been reported to accumulate in agricultural fields under continuous plastic mulching, as well as their subsequent absorption and accumulation in cultivated

plants (Rodrigues *et al.*, 2019; Peng *et al.*, 2020). Inhibition of plant development in several cultivated species has been reported (De Souza Machado *et al.*, 2018).

Environmental and economic issues of removal and disposal of used agricultural plastic vary depending on the modes of disposal, such as landfilling, open burning, onsite dumping, recycling, or incineration (Schwabl *et al.*, 2019).

To sum up, to date repeated application of plastic mulches is resulting in the release and accumulation into the soil of a complex mixture of fragments and chemicals with potentially harmful effects. As the world is comprised of interdependent dynamic systems, consequences of using plastic mulches are not restricted to agricultural soils but also threaten natural ecosystems, as elements from one system, including plastic wastes, may migrate from agro ecosystems to natural ecosystems (Wong *et al.*, 2020; Serrano-Ruiz *et al.*, 2021). Despite the evidence for this, the fate of released plastic mulch fragments, compounds and other contaminants they carry has been scarcely monitored (Wong *et al.*, 2020). Overall, repeated application of LDPE mulches is leading to a scenario of persistent plastic fragments and chemicals, accumulating year after year into agricultural soils and compromising agricultural soil health, food security and environmental sustainability (Zhang *et al.*, 2020; Serrano-Ruiz *et al.*, 2021). For all these reasons, substitutes for plastic are desirable.

#### **4.1. Alternatives to polyethylene plastic mulch:**

Paper mulches may offer a solution to the problem of disposal of plastic mulches, since they can decompose fully after use and be incorporated into the soil. Paper mulches have since been evaluated with varying results. Newspaper mulches represent an available and cost-effective resource and have been frequently trialed. Although paper mulches are cheaper than biodegradable mulches, they are more expensive than plastics, their life span is shorter and they may expand and contract in ways that cause problems to the crop plants (Miles *et al.*, 2017). Coolong (2010) showed the potential of paper-based mulches for use in vegetable production systems. Where, further developed the method of using paper mulches together with direct seeding. Heat-melting glue was used to adhere the sheets of non-woven mesh and recycled paper and to support the grains of rice in the holes so they could germinate and grow at planting density. In this way, the mulch can control weeds so that herbicides are not required, it saves labor, it does not require special equipment, and transplanting is not needed.

Sanchez *et al.*, (2008) reported success when using shredded newspapers as a weed-suppressing mulch in organic high-tunnel cucumber (*Cucumis sativus*) production. However, some paper mulches deteriorate rapidly under field conditions, reducing their effectiveness.

Paper mulches have been considered for use in fruit and vegetable production since the early 20<sup>th</sup> century. Although paper mulches were once widely used in vegetable crop production, their use waned as the many benefits of polyethylene mulches made them a more suitable choice for farmers. Recently, there has been interest in paper mulches because they are biodegradable, are manufactured from a renewable resource, and do not have to be removed from the field after harvest. The recently results suggest that paper-based mulches have potential for some vegetable production systems (Kader *et al.*, 2020; Serrano-Ruiz *et al.*, 2021).

#### **5. Biodegradable and photodegradable plastic mulches:**

Researchers worldwide are interested in the area of biopolymer development. Also the governments have stringent regulations in place regarding acceptable emission levels. For this reason, many material scientists and engineers have focused their work on environmentally stable biodegradable plastics. Biodegradable plastics have been proposed to decrease the accumulation of LDPE and other persistent plastic wastes in the environment. Worldwide, governments and companies are promoting the development of biodegradable plastics, including mulches, while taxing or banning non-degradable plastic utilities (Hu, *et al.*, 2020; Serrano-Ruiz *et al.*, 2021). Biodegradable mulches (BDMs) must also fulfil properties similar to LDPE ones during their service. (BDMs) are designed to be later tilled into the agricultural soil, where native microorganisms are to break down and use the mulch polymers (Bandopadhyay, *et al.*, 2018). They are aimed to save time and cost in collecting and managing plastic fragments and to avoid waste generation.

Recently, biodegradable mulch films have been viewed as a more sustainable ecological alternative to plastic polyethylene mulch. Biodegradable plastic mulch first was synthesized in the mid-1970s (Albregts and Howard, 1972; Otey *et al.*, 1974). However, early biodegradable mulches broke down

only partially (Kasirajan and Ngouajio, 2012). Although some commercially available mulches are compostable, reliable in-soil degradation of plastic mulches has not yet been achieved. Biodegradable mulch films theoretically can save significant labor and disposal costs through incorporation via soil tillage operations rather than disposal in landfills (Brodhagen *et al.*, 2017). By definition by the American Society for Testing and Materials (ASTM), biodegradable plastics are broken down by naturally occurring microorganisms (ASTM, 2012a), and ultimately converted to carbon dioxide and water under aerobic conditions (Kasirajan and Ngouajio, 2012).

Biodegradability is an end-of-life option that allows one to harness the power of microorganism present in the selected disposal environment to completely remove plastic products designed for biodegradability from the environmental compartment via the microbial food chain in a timely, safe, and efficacious manner. Terms like “oxo”, “hydro”, “chemo”, “photo” degradable describe abiotic (nonbiological process) mechanisms of degradation. They do not constitute or represent “biodegradability” the biological process by which microorganisms present in the disposal environment assimilate/utilize carbon substrates as food for their life processes.

Oxo-biodegradable (OXO) plastic is a polyolefin plastic to which amounts of metal salts have been added. The mechanism of its degradation known as “oxobiodegradation” is to promote, first, abiotic (photo or thermo) oxidation and second, microbial biodegradation (Kasirajan and Ngouajio, 2012; Brodhagen *et al.*, 2017; Serrano-Ruiz *et al.*, 2021). See Fig.4.-

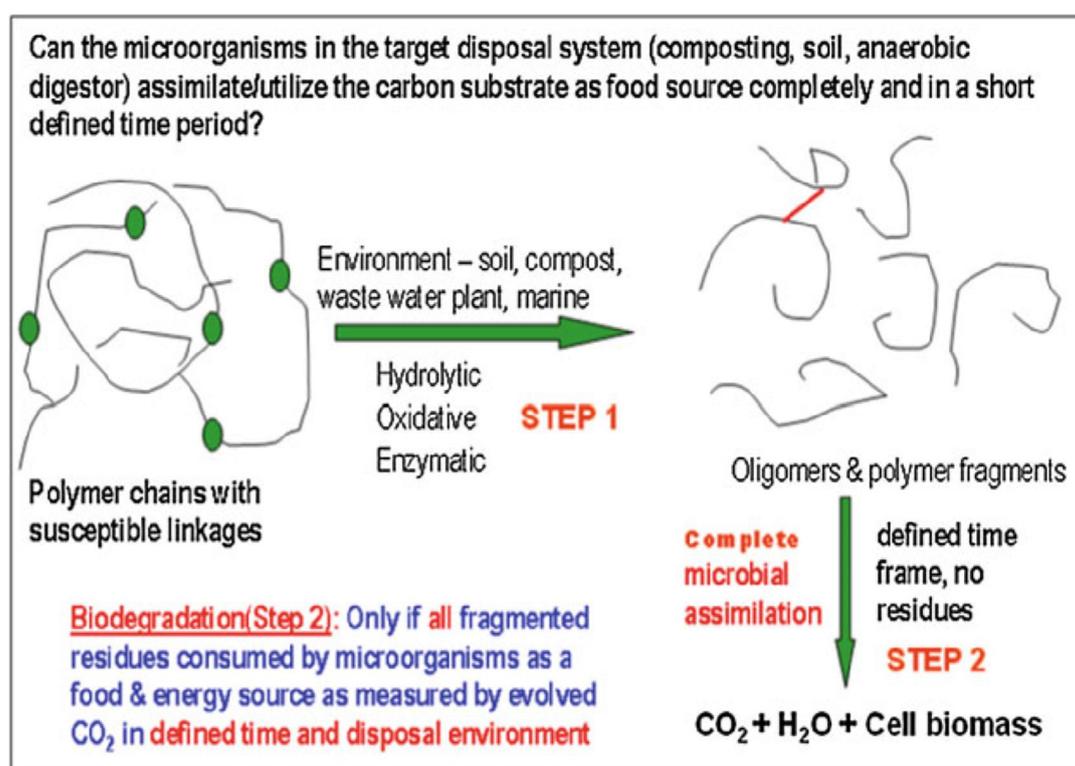


Fig. 4: Understanding the biodegradability process (Serrano-Ruiz *et al.*, 2021).

Oxo-biodegradable materials behave similarly to photodegradable materials, i.e., the buried part does not suffer degradation and needs to be exposed to light and air because the degradation of oxo-biodegradable plastics is a result of oxidative and cell-mediated phenomena, either simultaneously or successively. Films made out of copolyester, sometimes with starch as an additive, are another option available in the market (Kasirajan and Ngouajio 2012)

Photo-biodegradable polyethylene films containing starch have been developed and used in agriculture. They are better able to raise temperature, preserve moisture, and raise yield than common polyethylene films and can be degraded environmentally after use. The photo-biodegradation induction periods of four kinds of photo-biodegradable polyethylene films range from 46 to 64 days, which basically satisfies the needs of agricultural cultivation. All photo-biodegradable polyethylene films can be degraded to stage V, in which almost no film exists on the surface of the ridges 2–3months or so

after the induction periods. The photo-biodegradable polyethylene films buried in soil have also good degradability (Kasirajan and Ngouajio, 2012; Horton *et al.*, 2017).

Biodegradable plastic mulches (BDMs) have been developed as substitutes to PE mulch films and are designed to be tilled into soil after use where resident microorganisms degrade the plastic. BDMs can be prepared from bio based polymers derived from microbes or plants, or fossil-sourced materials (Miles, *et al.*, 2017). Common biobased polymers used in BDMs include polylactic acid (PLA), starch, cellulose, and polyhydroxyalkanoates (PHA). Fossil-sourced polyesters used in BDMs include poly (butylene succinate) (PBS), poly (butylene succinate-co-adipate) (PBSA), and poly (butylene-adipate-co-terephthalate) (PBAT) (Kasirajan and Ngouajio, 2012). Polymers used in BDMs contain ester bonds or are polysaccharides, which are amenable to microbial hydrolysis (Brodhagen *et al.*, 2017). In theory, BDMs should be completely catabolized by soil microorganisms, converted to microbial biomass, CO<sub>2</sub> and water (Kasirajan and Ngouajio, 2012; Brodhagen *et al.*, 2017). In practice, complete breakdown in a reasonable amount of time is not always observed. Regulators and growers cite concerns about unpredictable or incomplete breakdown and the ultimate fate of BDM constituents and their effect on soil ecosystems (Goldberger *et al.*, 2015; Miles *et al.*, 2017). Due to increased demand for eco-friendly substitutes to PE, the global market for BDMs is expected to continue to grow. Soil health is a key component of agroecosystem sustainability, thus there is a need to understand the effects of BDMs on both crop productivity and soils. To date,

### **5.1. Properties and composition of biodegradable plastic mulches:**

Suitable alternative methods for the disposal of plastic films include the use of biodegradable materials (Goldberger, *et al.*, 2015; Hayes *et al.*, 2019; Ghimire, *et al.*, 2020). At the end of their life, biodegradable materials can be integrated directly into the soil where microflora transforms them into carbon dioxide or methane, water, and biomass. Because biodegradable materials do not produce wastes that require disposal, they could represent a sustainable ecological alternative to low-density polyethylene films (Brodhagen *et al.*, 2017).

The monomers building the polymer backbone provide for the main properties of the mulches, such as physical resistance and low water vapor transfer, and for their biodegradability. For a plastic polymer to be biodegradable, extracellular enzymes from microorganisms are to break the monomer bonds of the polymer chain, and the released monomers are to be used by microorganisms to growth, eventually resulting in the mineralization of the polymer molecules to their basic compounds, CO<sub>2</sub> (CH<sub>4</sub> under anaerobic conditions), H<sub>2</sub>O and minerals, increasing microbial biomass and with no plastic waste remaining into the soil (Kasirajan and Ngouajio 2012; Brodhagen *et al.*, 2017). Agricultural biodegradable plastic mulches must accomplish biodegradation by native soil microorganisms and in the agricultural soil.

To achieve biodegradation, hydrolysable bonds between the polymer monomers are required, and the released monomers are to be used as energy and carbon source by soil microorganisms to grow. The biodegradation process involves three main steps: (1) microbial colonization of the polymer surface, mainly bacteria and fungi, (2) depolymerization by extracellular microorganism enzymes and, (3) microorganism consumption of the hydrolysis products (Serrano-Ruiz *et al.*, 2021). Factors driving microbial metabolism and affecting biodegradation rate (e.g. oxygen, water and temperature) have already been addressed and reviewed (Brodhagen *et al.*, 2017; Ahmed *et al.*, 2018; Bandopadhyay *et al.*, 2018). Several polymers accomplishing the properties BDMs require have been identified, together with their main characteristics, and are already used for production of biodegradable plastic mulches. The main commercial biodegradable plastic mulches, together with their performance in crops, have been reviewed by Bandopadhyay *et al.*, (2018) and Serrano-Ruiz *et al.*, (2021).

Biodegradable plastics have been developed from early 1980s particularly biodegradable aliphatic polyesters (e.g., polyhydroxybutyrate or polylactic acid) or starch-polymer blends. However, the high cost of these polyesters prevents their commercialization. Also the starch-polymer blends are actually not 100% biodegradable. Starch-based mulch films have become popular in current research because starch is an inexpensive and abundant natural polymer that can produce a film structure (Brodhagen *et al.*, 2017). Barragan *et al.*, (2016) developed a biodegradable film from a blend of starch and biodegradable polyester polymers. Acceptable behaviors of the films have been achieved for general uses.

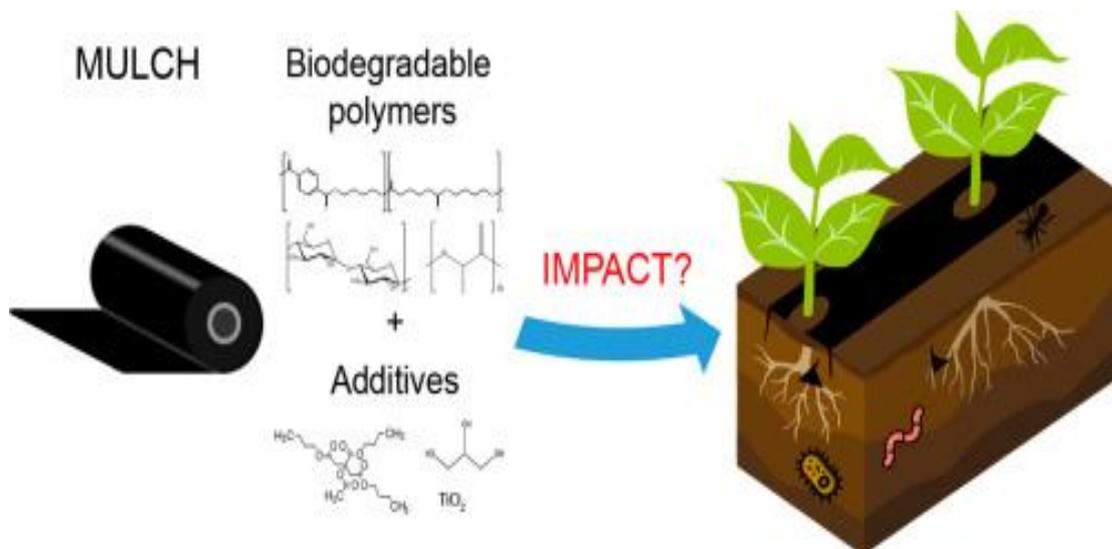


Fig. 5: Biodegradable plastic mulches (Serrano-Ruiz *et al.*, 2021).

### 5.2. How Biodegradable Plastic Mulches are Made:

Most biodegradable plastic mulches that are currently available commercially are made from plant starch. Agricultural films made of starch are prepared using conventional plastics processing technology. However, due to the poor mechanical properties of starch, including its brittleness, it must be blended with other polymers and/or plasticizers. Products currently on the market that are derived from or blended with plant starch include Biosafe™ (Hayes *et al.*, 2019).

Two polymers that may have a role in biodegradable plastic mulches in the future are polylactic acid (PLA) and polyhydroxyalkanoate (PHA). PLA is a highly versatile, biodegradable polyester derived from 100% renewable resources such as corn and sugar beet starch, and offers great promise in a wide range of commodity applications (Drumright *et al.*, 2000). Starch is converted by microorganisms into lactic acid through fermentation. Lactic acid molecules are then linked together into long chains called polymers. PLA is a relatively inexpensive biopolymer to manufacture and can be produced in large quantities. The PLA polymer is highly attractive for biological and medical applications because it can be spun into filaments that can be used to make textiles or films (Gupta *et al.*, 2007). PHAs are promising biodegradable plastics that have been highlighted as “green” polymers because they are made from renewable resources in a one-step process through bacterial fermentation of sugars and/or lipids (Goldberger *et al.*, 2015; Hayes *et al.*, 2019; Ghimire *et al.*, 2020). PHA polymers may be produced from microbes or plants, but currently, microbes are the primary source (Bandopadhyay *et al.*, 2018).

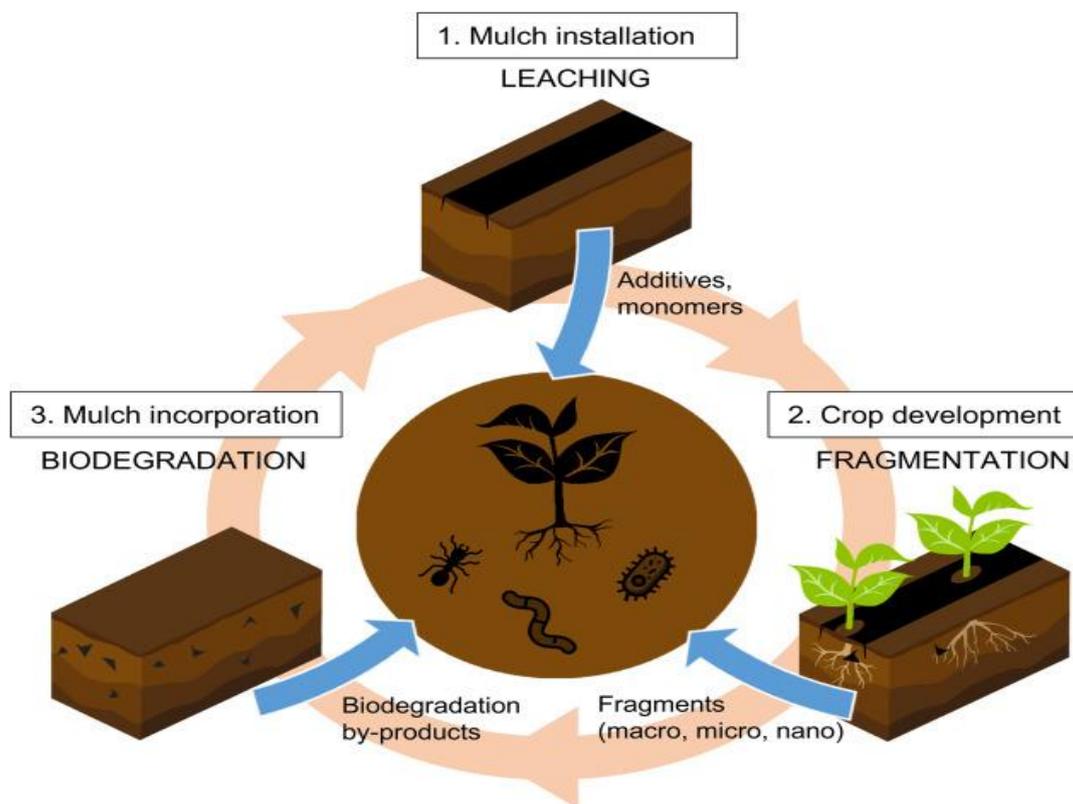
### 5.3. Mulch after the crop harvesting: incorporation into the soil

Biodegradable mulches are tilled into the soil shortly after the crop cycle ends; later on, a new crop and mulch cycle will start. Mulch biodegradation by soil microorganisms becomes massive and the buried mulch macro, micro and nanofragments continuously release additives, monomers, and by-products from the biodegradation process. These components accumulate and continue to biodegrade until their complete mineralization to CO<sub>2</sub> and H<sub>2</sub>O.

For plastic mulches to be considered biodegradable, criteria from international standards (EN 17033, 2018) require films or their base material in its primary form (i.e. powder) reach at least 90 % biodegradation in < 2 years in natural topsoil from an agricultural field or forest, in aerobiosis at 20–28 °C. However, even when BDMs accomplish these requirements, a fraction of the BDM may accumulate in soils when continuously applied (Miles *et al.*, 2017). Several studies addressing the in-soil biodegradation under controlled laboratory conditions demonstrate the process to be strongly dependent on the material nature, fragment size and on the incubation conditions, such as the temperature, pH, humidity, oxygen level, and nutrient availability. However, in natural settings these conditions vary strongly depending on location, climate, soil type and depth (Haider *et al.*, 2019; Serrano-Ruiz *et al.*, 2021).

## 6. Ecotoxicity estimation of biodegradable plastic mulches

The ecotoxicity estimate of a marketable product is fundamental to prevent environmental and health risks. The assessment is specifically relevant for biodegradable plastic mulches, materials completely and repeatedly incorporated into the agricultural soil. In contrast with LDPE films, which after their end-of-life cycle are to be retired from the field and enter the waste management system, BDMs, i.e. all their compounds, are released into the soil and put in direct contact with native soil organisms and with cultivated plants Fig 5.



**Fig. 6:** Agricultural cycle of biodegradable plastic mulch films during time of use (Serrano-Ruiz *et al.*, 2021).

The research on ecotoxicity assessment of biodegradable plastic mulches and of their components has typically been evaluated by their adherence to biodegradation and ecotoxicity standards (Hayes *et al.*, 2019). In the last six years, along with the escalation in diversity, availability, commercialization and use of biodegradable plastic mulches, there has been a rising interest towards deeper understanding of the effects of biodegradable plastic mulches on agroecosystem organisms (Bandopadhyay *et al.*, 2018). But research in this area is still in its infancy. Barely a few publications have tested for effects of biodegradable mulches on a small number of plant species and on soil microorganisms. To date, studies have been limited to those conducted by (Haider *et al.*, 2019; Serrano-Ruiz *et al.*, 2021).

## 7. Conclusions and future trends

The increasing use of biodegradable plastics for agricultural mulching as an alternative to conventional non-degradable LDPE film mulching is highly valued to alleviate plastic pollution, but still entails iterative incorporation of these mulches into the agricultural soil. Dynamics of the biodegradation process involve mulch fragmentation, release of compounds and consumption of plastic constituents by the soil microbiome. Migration of mulch compounds to the environment may start from the time the mulch is placed on the soil at the beginning of the crop season. Impacts of biodegradable mulches on cultivated plants and on soil organisms remain mostly uncovered, the mulch composition playing a major role, as well as the diversity of the environmental conditions in which they are used. Plastic fragments themselves have also an impact, with effects of their size poorly known but pointing to higher impact of microplastics on plants than on other soil organisms. To our knowledge, no reports

have been produced on the impacts of nanoplastics from biodegradable mulches on plants or on soil microorganisms.

Finally, migration of compounds and chemicals released from the films beyond the agricultural system to other compartments, including natural ecosystems, should be considered. Special attention is also to be paid to avoid the incorporation of chemicals and other components susceptible of being transported and accumulated within the food web that could jeopardize and risk human health. In-depth research on the effects on living organisms emerging from using biodegradable plastic mulches is required to guarantee the environmental safety and sustainability of these materials.

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