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Review

The Biodegradability of Plastic Products for Agricultural Application: European Regulations and Technical Criteria

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Abstract: Plastic products are used in agriculture to increase crop yield and improve crop quality to face a double challenge: a growing world population and a depletion and scarcity of natural resources. In this framework, the European Commission is working on establishing biodegradation criteria under natural conditions for certain plastic products. Such criteria are particularly important for products where biodegradation is key once reaching the end of their shelf life, considering an end-of-life scenario where their waste management is either unfeasible or highly complex. Under this scope, this work aims to provide a comprehensive assessment of the current status of European regulations in terms of plasticulture product biodegradability, highlighting the specific tests and standards regarding the biodegradability assessment. Biodegradation of plasticulture products in soil and water has been considered for biodegradability criteria, establishing a threshold of at least 90% of the organic carbon converted into CO_2. These regulations have followed a tool-based study of a mathematical prediction model for the main existing families of biodegradable polymers in soil. These regulations will help the fertilizer industry to develop new formulations that are more sustainable and effective in the agriculture field.

Keywords: plasticulture; mulching film; control release fertilizer; agriculture; biodegradation; EU regulatory framework; standard tests; microplastics; sustainability

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1. Introduction

It is predicted that the world's population would rise to nearly 10 billion people by 2050, increasing by one third, or 2.3 billion, despite a slower growth rate than in the previous four decades [1,2]. Food demand is anticipated to increase as the population continues to grow, which results in a considerable need to improve agricultural productivity [3]. Specifically, plasticulture has been a true revolution in the agricultural world and society in general, allowing many lands that lacked agricultural potential to be transformed into highly productive farms. The versatility of plastics used during the cultivation phase makes them ideal for multiple applications: agricultural films (greenhouse, mulching, micro- or polytunnels, and silage); crop protection nets; waterproofing sheets for reservoirs and slurry pits; irrigation systems (tanks, pipes, tapes, drippers, filters, etc.); seedbeds and cultivation trays; twines and fastening clips, among others [4]. In this way, thanks to plastic materials, traditional agriculture has shifted from being a marginal sector to becoming the main economic source for many traditionally disadvantaged populations and regions. In 2022, Plastics Europe estimated that the agricultural sector represented roughly 4.7% (2.5 million tons) of the European demand for plastics [5]. Agriculture Plastic & Environment Europe (APE Europe) estimated that in 2019 around 722 kilotons (Kt) of plasticulture products (not considering packaging) were marketed in Europe, where the use of agricultural plastics rose by almost 7% between 2015 and 2019 [6].

Factors such as the decrease in available agricultural land and the demand for high-quality crops have highlighted the necessity of using agricultural plastics, increasing the consumption of these products (especially the ones with improved properties and low-impact) [7].

Regarding the application of plastics in agriculture, in 2019, the most used product in Europe was film, being approximately 76% of the total agricultural plastics marketed. The remaining market included stakes (11%), nets (8%), and pipes (5%). The development of plasticulture in Spain serves as an example for many countries: the estimated average volume of agricultural plastics is 181,970 tons (t), with agricultural films (53%), irrigation pipes (43%), stakes, and cords (4%) being the main applications [8].

The practices related to the intensive use of plastics in agriculture must be demanding in terms of the safety and sustainability of their products. Indeed, giving up on their use is not an option due to the great advantages they bring to the sector. Plastic waste reduction and avoidance are becoming increasingly significant on a global scale, both in environmental policy and as essential components of the shift to a green economy. In Europe, the direction toward waste prevention and reduction has been marked through the "Roadmap to a Resource Efficient Europe" plan [9] and the European Commission Communication "Towards a circular economy: A zero waste programme for Europe" [10].

As well as packaging, the agricultural sector needs to consider the product design approaches, not only for the final product but also for the processes followed to obtain it. These strategies aim to reduce the quantity of material required for the product itself as well as to reduce materials with hazardous substances or difficult to recycle. In addition, the reduction in microplastics leaked from these products is also rising as an important aspect to consider during the design of the product [11].

In 2022, the agriculture sector has generated 4.6% (1.5 million tons) of plastic waste collected in Europe [5]. The wide number and types of plastic products have an important role in the generation of plastic waste from the agricultural sector, not only for their potential environmental impacts but also for the current lack or impossibility of recovery systems for some waste at the end of its life (e.g., plastic component materials of a fertilizer to carry out its nutrient release function in the soil).

The main pillars of the strategy to reduce the environmental impacts of agri-plastics are prevention (eco-design), correct management, and reduction in waste generated from the agricultural sector [12]. Among the possible strategies, the main ones are the selection of low-impact materials and avoiding incorrect practices at the end of the product life (such as burning, burial, and abandonment).

In the early stages of the eco-design of a product, the objective is focused on selecting formulations that do not contain toxic and dangerous substances and/or using biodegradable bioplastics in applications where the environmental benefit is demonstrated [13]. It is possible to identify several features shared by various applications that make them suitable candidates for replacement with biodegradable plastics. These include a short to medium lifetime in the field, typically ranging from one to three seasons (up to three years). Post-consumer plastic waste is often characterized by a high contamination of soil or plant residues (e.g., mulch film, geotextiles in reforestation or landscaping), making recycling challenging and, in many cases, not economically viable [14,15]. Furthermore, for plastic waste that cannot be separated from the soil (such as hydrogels or controlled-release fertilizers), biodegradable polymers may be able to lessen the overall environmental impact of certain agricultural plastic applications.

This paper aims: (i) to provide a comprehensive review of the current situation of agricultural plastic products, with a focus on their legislation; (ii) to help professionals from both academic and industrial sectors to properly manage this topic; and (iii) to enhance and promote awareness on this topic of the scientific and public community.

2. Agriculture Biodegradable Products in the Market

Agricultural plastics in Europe play a vital role in enhancing productivity, protecting crops, and improving resource efficiency. Commonly used plastics include polyethylene (PE) for greenhouse films, mulching films, silage wraps, and stretch films; polypropylene (PP) for woven sacks, ground covers, and big bags; and polyvinyl chloride (PVC) for irrigation pipes or generally water management systems [16]. These plastics serve various purposes, such as controlling soil temperature and moisture, reducing weed growth, and ensuring the long-term preservation of fodder, among others. Advanced plastics like ethylene-vinyl acetate (EVA) and polycarbonate (PC) are gaining traction for their improved durability and flexibility, especially in greenhouse applications [17,18]. Europe emphasizes sustainable practices, leading to increased adoption of biodegradable mulching films and recycling initiatives to mitigate environmental impacts.

Many of these applications only last for a short time—on average, a little more than two years—and produce considerable amounts of waste at the end of their life, which needs to be properly disposed of, as in the case of plastics for soil nutrient control release and/or mulching film [19].

On one hand, an effective way to have a sustainable agriculture system is to use the same agricultural areas while improving the performance of the crops by giving the plant the nutrients it needs to grow. Agricultural and livestock supplies are a fundamental aspect to improve crop yield, being essential products to carry out the planting, management, and harvesting of crops [20]. These fulfil various functions of great relevance in agricultural management, such as soil preparation, plant nutrition, protecting crops from possible pests, and improving the quality of crops. In order to replenish the nutrients that were taken out during the harvest, fertilizer must naturally be applied to the agricultural area. In addition to replenishing fundamental nutrients like nitrogen, phosphorous, and potassium, modern fertilizers typically supply secondary nutrients like calcium, magnesium, and sulphur, and trace nutrients like iron, manganese, and others [21]. However, an excessive use of fertilising products causes issues like eutrophication and contamination of natural waters, having a secondary effect on human health and sustainability [22], as well as deteriorating food quality and soil fertility after a long use [23].

Fertilisers can generally be divided into organic and chemical according to their origins (biological or synthetic, respectively) [24], with the first being less efficient in terms of productivity achieved if compared to the latter. Among them, fertilizer efficiency can be enhanced by a fertilizer release that occurs more gradually. This can be done through several methodologies, such as coating layers, mechanical and melt processing, spray drying and coacervation, and using various materials like fibre, clays, porous materials, polymers, or a combination of them [25].

Compared with traditional EU fertilising products, those made with polymers could improve nutrient usage and offer advantages in terms of product efficiency by using control release mechanisms of dosage. The use of polymers is crucial for the functioning of a nutrition product. It improves the efficiency in the framework of transitioning to more sustainable and environmentally friendly agricultural practices, according to the objectives of the Common Agriculture Policy (CAP). For example, a polymer coating forms a barrier for moisture to limit water penetration and thereby prevents the fast release of nutrients [26]. Over time, temperature and moisture are factors triggering the release of the nutrients [27]. Combining polymers with fertilizers can reduce the amount of fertilizer application rates by up to 66% compared to conventional fertilization applied to the soil, so-called overhead fertilization [28]. In addition, polymer coatings decrease the phytotoxicity of nutrients to plants and reduce the fixation of nutrients in soil by limiting precipitation with or absorption to minerals [29], e.g., the precipitation of phosphate with calcium to form calcium phosphate. The use of control release fertilisers (CRFs) contributes to keeping nutrient concentrations in soil. This is an example of containing relevant polymers other than nutrient polymers, which can act as coating agents or improve the water retention capacity or wettability. Additionally, CRFs enhance the quality of plants that require a steady, low-rate supply of nutrients. Despite lower fertilising product application rates, the increased nutrient use efficiency allows maintaining or increasing crop yield [30]. CRFs decrease the number of applications needed for a well-matched nutrient supply. Thus, the use of CRFs reduces the amount of fertilising volume as well as labour costs compared to conventional fertilizing practices.

Mulching is a technique that involves covering the soil with different materials, mimicking the presence of leaves and woody debris sediments in the soil. This technique inhibits the growth of weeds due to the combined action of the biochemical breakdown of organic materials and the blockage of solar radiation. Mulching was done using a variety of materials, like straw, dried leaves, tree bark, cardboard, gravel, lapilli, jute, cocoa husks, natural fibres (mostly coconut and hemp), and organic waste, prior to the invention of plastic films.

The agricultural community took a keen interest in plastic mulching films. They protect the soil from erosion caused by the rain, keep it moist, and block the sun's rays to prevent weeds from growing [31]. With the help of specialized equipment, plastic films may be easily applied to the soil, quickly covering tens of hectares. In accordance with the needs of the crop, the location, and the growing season, plastic mulching films must also ensure their mechanical and physical performance throughout the entire crop cycle [32]. They must be manageable during the soil-settling phase and have a lifespan that should allow for their simple removal from the soil at the conclusion of the crop production cycle.

The awareness related to the environmental problems caused by the wide use of non-biodegradable petroleum plastics and bad human practices arises from the marked drawbacks of plastic film disposal options after their lifetime. At the end of cultivation, plastic mulching films are contaminated with soil, pesticides, fertilising products, and biological waste up to 40–50% by weight [9]. Due to the acceptance limit of a maximum of 5% contaminants by weight for plastic film recycling [33], cleaning and recovery of agricultural plastic film take too much time, manual labour, and consequently, unaffordable expenses for farmers. Furthermore, the plastic films undergo a photo-degradation process during field exposure [34], which lowers film performance but does not affect the films' permanence in the soil [35]. Regular collection, disposal, and recycling processes of films can be occasionally costly. For this reason, plastics are frequently dumped in public landfills, on the side of the road, or, worse, burned, which releases harmful chemicals into the air and soil [36].

3. Biodegradation as End-of-Life of Agricultural Plastics Products

Generally, biodegradation is a beneficial property for the several materials and products from a technical, environmental, and economical point of view [37], for example, those whose final application occurs or ends up in the soil (agriculture mulching film, horticulture pots, etc.) or water (cosmetics, fishing gears, etc.). As previously mentioned, sometimes the recovery or recycling of these products from the soil or water is not viable due to their contamination with soil and their loss of mechanical properties and fragmentation in the environment. To lessen the detrimental impacts of land overuse and improve the sustainability of agriculture, it is crucial to promote the idea of biodegradability.

Biodegradation is the breakdown of an organic, carbon-based compound to CO_2 (and, eventually, CH_4 in anaerobic conditions) and water. In that sense, biodegradation can be considered as degradation on a chemical level, different from disintegration or fragmentation, which is a physical degradation.

The biodegradation reactions under aerobic and anaerobic conditions can be schematized in the following equations.

Aerobic biodegradation

$$C_{polymer} + O_2 = CO_2 + H_2O + Biomass + Residue \quad (1)$$

Anaerobic biodegradation

$$C_{polymer} = CH_4 + CO_2 + Biomass + Residue \quad (2)$$

The organic carbon in the polymer is primarily converted into CO_2, and a small portion is transformed into microbial carbon (the so-called biomass yield) or results (partially or incompletely) undegraded. The level and rate of biodegradation are strongly dependent on environmental factors such as moisture content, temperature, types, and concentration of microorganisms and by the characteristics of the material that biodegrades (shape, hydrophobicity, molecular weight, etc.).

The biodegradation rate is strongly dependent on the type of polymer and the environment in which the biodegradation takes place, so the behaviour of biodegradable biopolymers changes depending on the conditions and the aggressiveness of the environment.

For this reason, a biodegradability statement must refer to a specific environment and product. This means that it is essential to use certified biodegradable materials under certain conditions when aiming to prevent the generation of microplastics by using low-impact materials in the agricultural sector.

The use of soil-biodegradable polymers is growing to replace agricultural applications made of conventional polymers. The agricultural market is a valid application for such products for the more complex recycling processes that these products face due to possible dirt and the level of contaminants. They also exhibit inefficient end-of-life recovery practices that involve the undesirable removal of organic and inorganic matter from the topsoil layers (contributing to soil depletion and desertification) and/or, simply, those that often cannot be recovered for management at the end of their life cycle (such as fertilising product coating agents, anti-caking agents, anti-dust agents, particles for enhancing the water retention capacity of products or soil, among others).

4. Regulatory Framework of Soil-Biodegradable Products

An EU fertilising product is made of component materials that meet the requirements for one or more of the component material categories (CMCs) set out and listed in Regulation (EU) 2019/1009 (hereinafter, the "Fertilising Products Regulation" or "FPR"), specifically in Annex II [38]. In the case of polymers, the Commission has considered the scientific opinions issued by the Committee for Risk Assessment and the Committee for Socio-Economic Analysis of the European Chemicals Agency in accordance with Regulation (EC) 1907/2006 [39]. On 29 January 2019, the Agency published the Annex XV dossier in the SEAC [40], concluding that the intentional use of petroleum-based polymer microparticles, leading to environmental releases, poses an environmental risk that is not adequately controlled and must be addressed at the EU level. According to the agency, almost 42,000 tonnes of intentionally added microplastics are presently released into the environment annually [41].

Subsequently, the Commission adopted the Regulation (EU) 2023/2055 [42], which introduces a common limitation in the aforementioned Regulation 1907/2006 for the marketing of synthetic polymer particles ("the general restriction"). In order to reduce needless releases, a complete prohibition on marketing was suggested for industries and uses where releases were thought to be inevitable, along with guidelines for consumption and disposal.

More specifically, the Annex XV dossier suggested prohibiting the sale of any solid polymer in microparticles or microparticles coated with a solid polymer, either alone or in combination, at a concentration of 0.01% or more by weight.

The Annex XV dossier proposed excluding degradable polymers (under certain biodegradability criteria) or water-soluble polymers and natural polymers without any chemical modification, since they have a reduced persistence in the environment and, therefore, are associated with lower environmental risks. Regarding degradability requirements, Annex XV sets specific criteria to demonstrate the degradability of polymers in products for agricultural and horticultural uses, where synthetic polymers are intentionally used and, by their nature, are considered microplastics by definition.

On one hand, Annex XV (point 2.1) refers to "fertilising products that contain polymers that are coating agents or enhance the water retention capacity or wettability of the product," meaning they perform a specific function after application to the soil. In this case, the degradability of the polymers, as defined in Article 2, point 1, of Regulation (EU) 2019/1009, will be demonstrated in accordance with the delegated acts referred to in Article 42, paragraph 6, of that Regulation.

The European Commission has established biodegradability criteria that these products must meet, based on the conclusions of a scientific-technical study developed from biodegradation prediction models [43]. These criteria are the ones established in Delegated Regulation (EU) 2024/2770 [44], which require relevant polymers to reach 90% degradation in soil after a maximum of 48 months from the end of the product's functional period. As for aquatic degradation, it must reach 25% degradation after a maximum of 12 months from the end of the product's functional time (in the specific case of a functional period of 6 months or more).

Additionally, the aforementioned Regulation (EU) 2019/1009 establishes the obligation for the Commission to evaluate the biodegradability criteria of mulch plastics in order to include them as a component material belonging to CMC 9. These criteria are the ones established in Delegated Regulation (EU) 2024/2787 [45], which require mulch films to reach 90% degradation in soil after a maximum of 24 months from the end of the product's functional time. As for aquatic degradation, it must reach 30% degradation within 12 months compared to that of a reference material, or a final degradation of at least 90% relative to the degradation of a reference material after a maximum of 24 months plus the product's functional period indicated on the label.

On the other hand, Annex XV (point 2.2) also refers to "agricultural and horticultural products other than fertilising products that contain polymers that are coating agents or enhance the water retention capacity or wettability of the product," meaning polymers that function as technical additives, such as anti-dust or anti-caking agents, which do not serve a function for a specified period after their application to the soil.

The degradability of synthetic polymer microparticles in products for agricultural or horticultural use other than the fertilising products referred to in point 2.1 shall be validated in (i) freshwater, estuarine, or marine water, and (ii) soil compartments.

To be considered degradable according to "*Entry 78—Rules on proving degradability*", a polymer in a product for agricultural or horticultural use other than a fertilising product mentioned in point 2.1 must reach 90% degradation in: (a) soil after a maximum of 48 months after the end of the product's functional time (the period after the application of the product and the duration of its function). (b) water after maximum: (i) 12 months plus the product's functional time, when test methods from group 4 (specifically, laboratory testing methods for polymers) are used; or (ii) 16 months plus the product's functional time, when test methods from group 5 (other types of simulated environment test methods) are used.

5. Standard Methods for Biodegradability Assessment

The biodegradation in industrial and natural environments is described in more than ten standards and norms [46–48], describing and harmonising the testing parameters, such as temperature, nutrients, pH, concentration of test substance, inoculum concentration and source, etc. The environments identified for the fertilising product end-of-life are the soil and water (both fresh and marine), whose standards are presented below.

5.1. Biodegradability in Soil

The ultimate biodegradability of plastic materials in soil is specified by the standard ISO 17556, "Plastics—Determination of the ultimate aerobic biodegradability of plastic materials in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved" [49]. This method is based on using the plastic sample as the main carbon source for the biodegradation in soil. The biodegradation is measured using either the oxygen demand or the amount of evolved CO_2 as the main parameter. When the biodegradation evolves, the microorganisms consume O_2 and produce CO_2. The oxygen demand can be determined through a manometric method, which converts the pressure drop from the CO_2 absorption into the oxygen demand. Alternatively, the evolved CO_2 can be determined through an infra-red (IR) sensor on the evolved gases, a gravimetric method, or by measuring the dissolved inorganic carbon of the basic solution used for adsorbing the CO_2. In any case, the air input on the reactor should be free of CO_2 to avoid error in the measurement.

Dark or diffuse light and environmental temperature (25 °C or in the range of 20–28 °C) should be adopted for the test. Test material (100–300 mg, preferably 200 mg) is mixed with natural soil (100–300 g, preferably 200 g); if the CO_2 detection method is used, a higher quantity of test material can be used. The test material can be used in any form, such as powder (maximum 250 µm), film, or pieces (maximum shape of 5 mm × 5 mm). A reference material such as microcrystalline cellulose or polyhydroxybutyrate (PHB) (in the same shape as the test material) is used to validate the biological activity of the soil. In addition, a blank reactor containing soil is used to know the background oxygen demand or CO_2 production of the soil. Triplicate for each test material reference and blank should be prepared. Humidity, the C:N ratio, and the pH of the test soil are adjusted to optimal values. Even if the normal testing period should be 6 months, the test should be carried out until reaching the plateau phase but no more than 24 months.

Biodegradation is calculated by comparing the oxygen demand or the evolved CO_2 with the respective theoretical values, according to the following formulas:

- For the oxygen demand:

$$D_t = \frac{B_{Tt} - B_{Bt}}{T \times fulllength\rho_T} \times 100 \quad (3)$$

where D_t = the percentage of biodegradation of test material at the time t; B_{Tt} = is the oxygen demand of the test material at the time t (mg/kg soil); B_{Bt} = is the oxygen demand of the blank at the time t (mg/kg soil); $fulllength\rho_T$ = test material concentration (g/kg soil); T = theoretical oxygen demand (mg/g test material).

- For the CO_2 evolved:

$$D_t = \frac{\sum m_T - \sum m_B}{ThCO_2} \times 100 \quad (4)$$

where $\sum m_T$ = amount of CO_2 in mg evolved from the test material at the time t; $\sum m_B$ = amount of CO_2 in mg evolved from the blank at the time t; $ThCO_2$ = is the theoretical CO_2 evolved from the test material in mg. The latter can be calculated with the mass of the test material m (mg) and the carbon content of the test material w_C (%):

$$ThCO_2 = \frac{44}{12} \times m \times w_C \quad (5)$$

The test is considered valid if a biodegradation of 60% or more is achieved for the reference material and the oxygen demand or evolved CO_2 values from each blank replicate have a deviation of less than 20% at the end of the test.

Alternatively, the soil biodegradability of plastic material is specified in the ASTM D5988-18 standard "*Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in Soil*" [50], equivalent to the ISO 17556. In this standard, the biodegradability is expressed by the CO_2 evolved from the test or, alternatively, by the O_2 consumption, as in the previous case. The ASTM standard specifies a reactor volume of 2–4 litres and provides slight differences on the environmental conditions of the test (moisture content should be 80 to 100% of the moisture holding capacity of the soil; C:N ratio of 10–20) and the amount of test material. In the same way, the validity criteria are different: the ASTM standard requires a minimum of 70% biodegradability of the reference after 6 months (the deviation of the values of the blank is maintained at 20% at the end of the test).

Focusing on biodegradable mulching film, the standard EN 17033 "*Plastics—Biodegradable mulch films for use in agriculture and horticulture—Requirements and test methods*" [51] specifies the requirements, criteria, and pass levels for these products. The standard defines specifications on the composition, biodegradation, ecotoxicity, and other properties (dimension, mechanical, and optical properties) of the mulching film. Concerning the properties, a biodegradable mulching film must have a limited presence of heavy metals and hazardous substances (according to a table provided in the standard) and a minimum content of 60% of volatile solids. A minimum level of biodegradation of 90% must be reached after a maximum of 24 months according to the ISO 17556. Finally, ecotoxicity will be evaluated on three species, such as higher plants, earthworms, and specific microorganisms (according to OECD 208, ISO 11268-1 or ISO 11268-2, and ISO 15685, respectively [52–55]) in order to cover all the possible exposure routes.

The biopolymers that have been recognized as soil biodegradable are natural and thermoplastic starch (TPS), poly(butylene succinate-co-adipate) (PBSA), PHB, and cellulose, while cellulose acetate and poly(butylene adipate-co-terephthalate) (PBAT) can be biodegradable in soil at certain grades [56]. A study by Narancic et al. [57] showed that among 15 samples of pure and blended biopolymers, only 6 fulfilled the biodegradability requirement of 90%. TPS, PHB, and polycaprolactone (PCL) achieved biodegradation after 136 days, while their blends obtained the same value after 256 or 347 days, leading to a conclusion of possible antagonism between them. Polyhydroxyalkanoates (PHAs) and starch-based bioplastics can achieve full biodegradation in soil after 3 months, but typically it occurs after 4–6 months [58–60]. In ref. [61], PCL resulted in fully biodegradable in soil conditions after 270 days at 22 °C, but more investigation on this polymer is still necessary [62]. It is widely known that the degradation of poly lactic acid (PLA) below thermophilic temperature (as in the case of soil environments) is almost negligible, and, in these conditions, PLA and PLA-based bioplastics do not comply with the soil biodegradability requirements since slight or no biodegradation has occurred after 200 days [63–65]. Also, although poly (butylene succinate) (PBS) is not a soil-biodegradable polymer [66], poly(butylene succinate-co-adipate) or PBSA have demonstrated a complete biodegradation in soil, as already pointed out by other research on how a higher adipate-to-succinate ratio results in a higher PBS biodegradation rate [67,68]. Choosing the right soil biodegradable polymer is crucial since mulching films are composed of a blend of thermoplastic starch and other polymers (PCL, PBAT, PBS, or PHA) to improve the poor physical properties of the starch [69].

5.2. Biodegradability in Marine and Fresh Water

Regarding marine water, the ASTM D6691 [70] standard focuses on the determination of the aerobic biodegradability of plastic material exposed to marine microorganisms existing in natural seawater. Plastic samples (usually 20 mg) in powder, film, pieces, or fragment forms are placed in a media (natural seawater inoculated with specific marine microorganisms) at 30 °C and 175 rpm rotation. Seawater can also be artificially prepared by mixing a specific amount of different salts (as listed in Table 1 of the standard) and at least 10 organisms between the species available. The generated CO_2 is measured through a respirometer to calculate the biodegradability degree as the proportion of the carbon of the polymer to CO_2 expressed as a fraction of the theoretical carbon of the test material. The test is considered valid if the biodegradation of the reference (cellulose, chitin, or kraft paper in the same form as the test material) is above 70% at the end of the test.

Table 1. Resume of the environmental parameters, biodegradability evaluation, and sample characteristics described in the soil biodegradability standards.

Condition	ISO 17556	ASTM D5988
Inoculum	Natural/artificial soil	Natural soil
Biodegradability parameter	Oxygen demand/CO_2 evolved	Oxygen demand/CO_2 evolved
Maximum testing time	6 months	Not specified
Temperature	20–28 °C	20–28 °C
Humidity	Not specified	80–100%
pH	6.0–8.0	6.0–8.0
C:N ratio	40	10–20
Amount of sample	100–300 mg	200–1000 mg C/500 g soil
Amount of inoculum	100–300 g	100–500 g

Regarding freshwater media, the ISO 14851 and ISO 14852 standards are used to assess aerobic biodegradability [71,72]. The main difference between these standards is the parameter used to determine the biodegradation: ISO 14851 considers the oxygen demand while ISO 14852 the CO_2 evolution. The test is performed in media (distilled water mixed with specific salts and nutrients), inoculated with an aerobic activated sludge from a wastewater treatment plant as inoculum. The sample to test (30–100 mg/L of total organic carbon; preferably in powder form with a maximum dimension of 250 µm, but other shapes are allowed) is mixed in a closed reactor with an inorganic media and the inoculum (obtaining a suspended solid range of 30–1000 mg/L), aerated with CO_2-free air (if ISO 14852 is followed) at 20–25 °C, and the biodegradability is monitored for the necessary period to reach the plateau phase, not exceeding 6 months. The medium should contain approximately 2400 mg/L of phosphorus and 50 mg/L of nitrogen, having a C:N ratio of 40 and a pH of 7. Triplicates of the test material and blank are necessary, while duplicates of microcrystalline cellulose powder or PHB are necessary for reference.

When the ISO 14851 standard is followed, biodegradability is determined by comparing the oxygen demand with the theoretical oxygen demand: the oxygen demand is determined by measuring the gas necessary to maintain a constant volume in the headspace of the reactor (due to the adsorption of the CO_2 evolved during the process) or measuring the variation of volume or pressure in the headspace. On the other hand, following the ISO 14852 standard, biodegradability is determined by comparing the amount of CO_2 evolved with the theoretical amount: evolved CO_2 can be measured by titrimetric determination or through an IR detector.

The biodegradation test is valid if (i) 60% of the reference has been biodegraded at the end of the test, (ii) a limited amount of CO_2 or oxygen demand has been evolved from the blanks at the end of the test, and (iii) the deviation of the blanks and test triplicates at the end of the test is lower than 20%.

The ISO standards are used to determine the disposability of plastics in wastewater treatment plants, according to the EN 14987 [73]. To ensure the suitability of this end-of-life, the samples must achieve a minimum biodegradation of 90% (in absolute terms or compared to the reference material) in 56 days, according to either ISO 14851 or ISO 14852. Additionally, the plastic material should have a solubility or dispersibility higher or equal to 0.9 according to the formulas described in the standard itself.

Being the water environment less aggressive than others in terms of biodegradation (e.g., compost), the numbers of biopolymers that are biodegradable in freshwater are less numerous than those that biodegrade in soil. Indeed, the same study of Narancic et al. [57] highlighted that, following the ISO 14851 standard (21 °C for 56 days), only PHB and TPS fulfilled the pass criteria. Blends of these polymers with polyhydroxyoctanoate (PHO), especially PCL, as well as pure PCL, obtained a biodegradation ranging from 50 to 70%, highlighting a propensity to freshwater biodegradation but not a fulfillment of the criteria. Yet, pure PLA or their blends showed a maximum of 15% biodegradation, confirming its limited biodegradation in unmanaged environments.

Apart from the above-mentioned standards, ECHA distinguishes 3 definitions of biodegradability for aerobic degradation: ready, inherent, and ultimate biodegradability. The ultimate biodegradability is the one presented above, in line with the ISO 14851 and ISO 14852 standards (where 90% of biodegradation is required after 6 months). On the other hand, ready and inherent biodegradability describe different processes and, as a result, have different durations of the test and percentages of biodegradation to reach [74]. Due to the limitation of standards, ultimate biodegradation can be assessed for both pure chemicals and complex multi-component materials such as polymers, while the inherent and ready biodegradability can be assessed only for pure chemicals or low molecular weight compounds, in general [75].

A material is considered readily biodegradable if it reaches a minimum biodegradation of 70% of DOC, or 60% of BOD, or evolved CO_2 in a 10-day window within 28 days, according to the OECD 301 standard [76]: positive results mean that the product can be labelled as "readily biodegradable" and "non-persistent". In general, the test substance is incubated at 22 °C with a mineral medium and an inoculum (activated sludge, sewage effluent, surface water, and soil, not pre-adapted to the test substance), evaluating the biodegradability parameters established by the standard. Blanks and reference samples are run in parallel, and each sample is evaluated at least in duplicate. The 10-day window begins when 10% of biodegradation has been achieved and must end before day 28 of the test. A test is considered valid if (i) the deviation of replicate values at the end of the test is less than 20% and (ii) the reference has reached the pass level by day 14.

Alternatively, OECD 301 proposes several tests according to the methods of organic compound removal (Table 2), such as measurement of dissolved organic carbon (DOC) (OECD 301 A, 301 E), evolved CO_2 (OECD 301 B), and biochemical oxygen demand (BOD) (OECD 301 C, 301 D, 301 F). The applicability of each standard depends on the characteristics of the material, such as solubility, volatility, and adsorbability (for example, DOC-based standards are not applicable for poorly soluble materials). It must be mentioned that CO_2 production and BOD consumption are very straightforward parameters for biodegradation, while DOC elimination only indicates the removal of carbon from the liquid phase. In order to account for the uptake of the test substance's carbon into the bacterial cells (a process that cannot be detected by measuring O_2 consumption and CO_2 production), the pass levels for naturally occurring biodegradation as determined by BOD and evolved CO_2 production are lower than those for DOC removal. [77]. Although the tests have different principles, results obtained by each method are equivalent even though the inoculum could affect the final result [78].

Table 2. Resume of the biodegradability evaluations and pass levels described in the water biodegradability standards.

Standard	Test Principle	Min. Biodeg.	Max. Time	Test Substance Concentration	Inoculum Concentration
OECD 301 A (DOC Die-Away)	DOC removal	70%	10 d *	10–40 mg DOC/L	≤30 mg/L SS
OECD 301 B (CO_2 Evolution (Modified Sturm Test))	Evolved CO_2	60%	10 d *	10–20 mg DOC/L	≤30 mg/L SS
OECD 301 C (MITI (I))	BOD reduction	60%	10 d *	100 mg/L	30 mg/L SS
OECD 301 D (Closed Bottle)	BOD reduction	60%	10 d *	2–10 mg/L	0.5 mL/L
OECD 301 E (Modified OECD Screening)	DOC removal	70%	10 d *	10–40 mg DOC/L	≤5 mL/L
OECD 301 F (Manometric Respirometry)	BOD reduction	60%	10 d *	100 mg/L	≤30 mg/L SS
OECD 302 A (Modified SCAS Test)	DOC removal	70%	14 d	20 mg/L	400 mg/L
OECD 302 B (Zahn-Wellens/EMPA Test)	DOC removal	70%	14 d	50–400 mg DOC/L	0.2–1.0 gDM/L
OECD 302 C (Modified MITI Test)	BOD reduction	70%	14 d	30 ppm (*w*/*v*)	100 ppm (*w*/*v*)
ASTM D6691	Evolved CO_2			160 mg/L	
ISO 14851	Oxygen demand	90%	6 months	30–100 mg TOC/L	30–1000 mg/L
ISO 14852	Evolved CO_2	90%	6 months	30–100 mg TOC/L	30–1000 mg/L

* within 28 days.

Lastly, a material is considered inherently biodegradable if it reaches a minimum biodegradation of 70% after 14 days according to the OECD 302 standards [79–81]. Inherently biodegradable is less stringent than readily biodegradable since the systems have a higher degradation power. For this reason, chemicals that fulfil the inherent biodegradability are considered biodegradable under several natural and industrial environments (such as wastewater treatment plants, WWTPs) and are considered non-persistent if some specific criteria are fulfilled. In this case, the standards have slight differences between them, mainly resumed in Table 2. Among the OECD 302 series, OECD 302B has the highest levels of simplicity and applicability. Following this standard, the test substance is mixed with a medium and an inoculum, then incubated at 20–25 °C and pH 6.5–8.0; up to 28 days. One or two 1.5 L reactors are used for the test substance and the blank, while only one reactor is needed for the reference. The liquid is sampled, and the DOC is measured: the test is valid if (i) reference reaches 70% of degradation within 14 days, and (ii) the removal of test substance takes place gradually.

6. Conclusions

Agricultural plastic products remain essential due to the numerous benefits they offer, including soil control, moisture retention, and crop protection, thus enhancing agricultural productivity. Indeed, promoting low-impact agricultural practices is crucial to achieving the second goal of the United Nations' 2030 Agenda, which aims to ensure sustainable and resilient agricultural systems. The challenge, therefore, lies in balancing agricultural productivity with the need to reduce environmental impact, integrating tools such as controlled-release fertilizers (CRFs) and mulching films made from biodegradable materials.

Future studies should focus on the use of biopolymers as a base for developing new agricultural plastic products while also regulating the discharge of plasticulture products to mitigate microplastic accumulation in soils. It is essential that biodegradable plastics meet both functionality and biodegradability requirements, ensuring that their natural breakdown rate aligns with specific soil conditions, climate, and crop nutritional needs throughout the growing cycle.

An in-depth assessment should be conducted over the entire lifecycle of these products to evaluate their true sustainability, although these evaluations face technical limitations, such as the difficulty of replicating complex environmental conditions and long-lasting tests in laboratory settings. In this regard, establishing standardized testing techniques at both national and global levels is critical for accurately assessing the actual sustainability of these products, ensuring their reliability and consistency under real operational conditions. Only through these coordinated efforts can the use of plastics in agriculture continue to support global food production while simultaneously reducing negative environmental impacts.

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