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Mulch Films: Degradation Analysis and Ecotoxicological Assessment in Marine and Terrestrial Environments

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Abstract

Agricultural soils have been identified as significant sinks for plastic waste from mulch films, which in turn can reach aquatic ecosystems. As an alternative to conventional materials, there has been growing interest in biodegradable mulch films, but their environmental behavior and ecotoxicological effects are not yet fully established. In this study, the effects of residues from a conventional mulch film and a biodegradable mulch film on model organisms representative of edaphic (*Hordeum vulgare* and *Cucurbita maxima*) and aquatic (*Paracentrotus lividus*) ecosystems were evaluated. During this study, the residues of the mulches in seawater were also analyzed, considering natural aging conditions, using pyrolysis-gas chromatography-mass spectrometry (Py-GC/MS). The results of the ecotoxicological tests showed that the residues of both types of mulch films did not generate any significant adverse effects on the selected terrestrial and marine bioindicators in the two end-of-life scenarios, with the exception of the residues of conventional mulch, unaged and aged for one month, at medium-high concentrations from an environmental point of view on *P. lividus*. The natural weathering assay in a marine environment showed that residues from conventional mulch film remained essentially unaltered, with similar concentrations detected throughout the 12-month exposure period. In contrast, the biodegradable mulch film exhibited significant degradation from the initial time point, reaching concentrations below the analytical detection limit after the first month.

Keywords: agriculture; mulch film; biodegradation; sustainable solutions; natural aging; detection method; standard test; toxicology; marine environment; terrestrial environment

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1. Introduction

The accumulation of plastic waste in aquatic and terrestrial ecosystems has become a growing environmental concern, highlighting the importance of monitoring its presence and developing effective strategies to reduce its negative impact on the environment [1–3]. Considering this, practices related to the intensive use of plastic products in agricultural soils must be subject to strict safety and sustainability criteria. In 2020, Plastics Europe estimated that the agricultural sector accounted for approximately 3.4% (1.7 million tons) of the total demand for plastics in Europe [4]; in addition, Agriculture Plastic & Environment

Europe (APE Europe) estimated that 722 kilotons (kt) of plasticulture products were sold on the European market in 2019. In terms of the application of plastics in this sector, mulch films accounted for the largest share in Europe, representing 76% of the total agricultural plastics sold in 2019 [5].

Conventional films, due to their thinness and prolonged exposure to the environment, tend to fragment and cause plastic waste to accumulate in the soil, deteriorating its agronomic quality [6,7]. This plastic waste can be transported by surface runoff or wind erosion into aquatic systems, contributing to pollution and putting associated ecosystems at risk [8,9]. Furthermore, at the end of the growing season, mulch films become contaminated with soil, biological residues, and agrochemicals, reaching up to 40–50% by weight, exceeding the residue limit allowed for acceptance in mechanical recycling processes, which makes their reprocessing unfeasible without complex and costly cleaning operations [10–12]. During collection, a considerable amount of soil adhering to the plastic is also dragged along, with an estimated 312 kt of soil being incorporated annually in the European Union, of which around 43% (133 kt) corresponds to mulch film. This represents a significant loss of soil organic carbon (SOC), negatively affecting soil fertility and structure, making it essential to minimize soil export associated with the removal of these products [13].

Given these environmental and operational challenges, biodegradation is considered a beneficial property, especially for products designed for direct application to soil [14]. Biodegradable plastic mulches (BDMs) are becoming established as a more sustainable technological alternative with performance equivalent to conventional plastic mulches in a wide variety of crops and conditions [15–18]. In this context, mulch film is the only agricultural product subject to specific regulatory requirements for biodegradability. According to Delegated Regulation (EU) 2024/2787, in the case of soil, the main environment in which it is used, plastic material must demonstrate 90% biodegradation within 24 months from the end of the product's functional life [19].

The degradation and transformation of plastic waste in the marine environment is a complex process influenced by various factors, such as salinity, biological activity, and mechanical forces. Current research is predominantly based on accelerated aging methods under controlled laboratory conditions to simulate environmental factors. For example, Zhu et al. (2020) [20] observed significant photooxidation and fragmentation of the surface of polystyrene (PS) plastic particles under simulated solar irradiation. These studies provide valuable information on the degradation mechanisms of plastic waste, but they may not fully capture the complex interactions present in natural marine environments. Research by Davies (2020) [21] emphasized that, while accelerated tests using high temperatures can induce significant degradation in short periods, they often introduce degradation pathways that do not exist in natural marine environments. Consequently, predictions from such tests may not accurately reflect the long-term behavior of plastic waste. Furthermore, Shi et al. (2024) [22] emphasized that the physical and chemical transformations induced by natural environmental aging are fundamental to understanding the environmental fate of this waste. They recommended the integration of advanced analytical techniques, which are essential for identifying aged plastic particles and their degradation products, such as pyrolysis gas chromatography/mass spectrometry (Py-GC/MS), Raman spectroscopy, and microscopy-based methods, in order to accurately characterize these transformations.

Despite these advances, long-term field studies examining the natural aging of plastic waste remain scarce, particularly in the case of biodegradable polymers. The lack of studies on natural aging in marine conditions not only limits our understanding of the environmental behavior of conventional and biodegradable plastic waste, but also hinders the development of robust risk assessments for marine ecosystems. To address these challenges, long-term in situ studies should be prioritized. These studies should integrate

advanced analytical tools, such as Py-GC/MS, to monitor degradation over extended periods and under natural marine conditions. Combining these efforts with findings from accelerated aging experiments will improve understanding of the environmental fate of plastic waste, ultimately guiding the development of effective mitigation strategies and policies to protect marine ecosystems.

The main objective of this study is to evaluate the effects of plastic residues derived from both conventional and biodegradable mulch films, prior to their use and after a period of conditioning and natural aging. These effects will be analyzed in organisms representative of different end-of-life scenarios: sea urchin larvae and higher plants, providing an integrated view of the environmental impact on both aquatic and terrestrial ecosystems. The study is complemented by the analysis of naturally aged plastic waste in marine conditions using advanced analytical tools such as Py-GC/MS.

2. Materials and Methods

2.1. Plastic Material

Two types of commercial polymers were used to obtain the residues from padded films: a conventional polymer and a biodegradable biopolymer in soil. The former corresponds to a thermoplastic grade widely used in the manufacture of mulch films, characterized by its mechanical properties and chemical resistance, and in accordance with the requirements of the UNE-EN 13655:2002 standard [23]. The second is a biodegradable grade used mainly for agricultural applications, which complies with the requirements set out in the UNE-EN 17033:2018 standard [24], relating to biodegradable mulch films used in agriculture and horticulture.

2.2. Biological Material

Adult specimens of *Paracentrotus lividus* were collected from a natural population located in the outer area of the Vigo estuary (Galicia, northwest of the Iberian Peninsula) during the period between May and August. A total of approximately 100 individuals, evenly distributed between males and females, were kept in 150 L tanks under natural photoperiod conditions and flowing seawater (14 $\pm$ 2 °C, pH 8.1 $\pm$ 0.1) until use. The sea urchins were fed a daily diet of green and brown algae, specifically *Ulva lactuca* and *Laminaria* sp.

The seeds of *Hordeum vulgare* and *Cucurbita maxima* were supplied by a company specializing in agricultural products. Before conducting the ecotoxicity test, a preliminary germination test was carried out in Petri dishes to determine their viability. Germination was evaluated in three independent replicates, all of which achieved rates above 70%, a value that guaranteed the suitability of the seed lots. Until use, the seeds were stored in their original sealed packaging.

2.3. Preparation of Samples for Ecotoxicity Tests and Analysis of Aged Mulching Film Residues

The mulch films, both conventional polymer and biopolymer, were subjected to a micronization process using a ZM 200 micronizer (Retsch GmbH, Haan, Germany). Subsequently, the fractions obtained were classified granulometrically using an AS 300 control sieve (Retsch GmbH, Haan, Germany), selecting the appropriate particle size ranges. Specifically, fractions with particle sizes between 125 and 250 µm, in accordance with ISO 10210, were selected [25] and used for ecotoxicity testing in terrestrial environments, while fractions with an average size of 40 µm were used for ecotoxicity testing in aquatic environments. Micronized plastic samples from both formulations were also used to analyze naturally aged plastic waste under marine exposure conditions.

To age the plastic particles for the marine ecotoxicity test and their subsequent Py-GC/MS analysis, two sterile glass bottles were filled with suspensions of the plastic particles in filtered seawater (FSW—1 µm-filtered seawater, sterilized with UV light and ozone (FSW, 30 psu salinity, pH = 8.1)). The concentration was 3 mg/L FSW. The bottles were kept under natural conditions (photoperiod, temperature) for one year, and aliquots were taken under sterile conditions at 0, 1, 3, and 12 months. In parallel, micronized samples of both types of mulch films were incorporated into the soil substrate at a concentration of 1% (*w*/*w*) in accordance with the criteria established in standard EN 17033. The resulting mixtures were subjected to controlled incubation periods of 0 and 3 months, following the methodological guidelines of standard ISO 20200 [26], with the aim of evaluating the possible effect of plastic material aging on the ecotoxicological behavior of the soil substrate. The choice of a three-month incubation period was based on previously reported evidence for the same biopolymer. In that study, its rapid degradation in terrestrial environments was demonstrated, as no film residues were detected in the soil after a period of 60 days [27]. After completing each incubation period, the soil samples were used in ecotoxicity tests in terrestrial environments.

2.4. Procedures for Biological Testing

2.4.1. Sea Urchin Embryo Test

Embryonic growth bioassays followed the methods described by Saco-Álvarez et al. (2010) [28]. The test was carried out using filtered seawater with suspensions of plastic particles from both types of mulch film described in Section 2.3. Each type of micronized plastic sample (conventional polymer and biopolymer) was analyzed at five concentrations: 0.0042 mg/L; 0.042 mg/L; 0.14 mg/L; 0.45 mg/L; 1.5 mg/L, corresponding to 30; 300; 1000; 3000 and 10,000 particles/mL, at each time point (0, 1, 3, and 12 months). The lowest concentration (0.0042 mg/L—30 particles/mL) reflects the levels typically detected in coastal marine waters, where concentrations in the range of 0.001 to 0.01 mg/L have been recorded. Intermediate and high concentrations (up to 1.5 mg/L—10,000 particles/mL) are commonly used in ecotoxicity studies as scenarios of intensified exposure, which allow for the analysis of sublethal effects and toxicity mechanisms under conditions of high stress [29]. This strategy allows the detection of dose-dependent responses and the determination of sensitivity thresholds in early stages of marine organism development [30].

To minimize genetic variation, sea urchin gametes were obtained from a single pair of mature *Paracentrotus lividus* individuals per experiment. Fertilization was achieved by adding 10 µL of undiluted sperm to a dense suspension of oocytes in 40 mL of seawater. Fertilization success and egg density were assessed by microscopic examination of three 25 µL aliquots. Fertilization rates consistently exceeded 99%, with a mean egg density of 7000 ± 200 eggs/mL. Within 30 min after fertilization, the eggs were transferred to 2.5 mL multiwell plates already containing the experimental treatments, at a density of 30 embryos/mL. Incubation lasted 48 h at 20 °C in darkness without aeration. Subsequently, the samples were fixed with three drops of 40% buffered formalin and examined under an inverted microscope (Axiovert 40 CFL, Zeiss, Spain). Size measurements were obtained from images captured using a DFK 42BUC03 camera system (Imagingsource®, Bremen, Germany).

2.4.2. Terrestrial Higher Plants Test

A seed germination test was carried out under controlled conditions. To do this, five milliliters of demineralized water were placed in Petri dishes containing a cotton base covered with filter paper. Fifteen *Cucurbita maxima* seeds and fifteen *Hordeum vulgare* seeds were placed on the filter paper and covered with a second layer of filter paper. The plates

were kept in darkness at room temperature. After five days, the total number of germinated seeds was recorded.

The bioassays on terrestrial plants were conducted in accordance with the procedures established in OECD 208 [31] and the modifications established in Annex B of standard EN 17033. Two plant species representative of different families were selected, one monocotyledonous (*Hordeum vulgare*) and one dicotyledonous (*Cucurbita maxima*). The test was carried out using the soil substrate obtained after each incubation period (0 and 3 months) with both micronized mulch films. The bioassay was carried out in pots containing 200 g of the soil substrate prepared for each experimental condition. Twenty-five seeds of the same species were placed on the surface of the substrate and covered with a thin layer of inert material (perlite). Three independent replicates were prepared for each sample. During the germination stage, the pots were kept in a phytotron in darkness at a temperature of 22 ± 5 °C and a relative humidity of 70 ± 5%. Once germination was complete, the pots were exposed to a photoperiod of 16 h of light and 8 h of darkness, maintaining the same temperature and humidity conditions, with a light intensity of approximately 3300 lux. The trial ended 15 days after 50% of the seeds germinated in the control pots.

2.5. Procedure for Analyzing Aged Mulching Film Residues

A gas chromatograph (8890A; Agilent Technologies, USA) equipped with a pyrolyzer and a mass spectrometer (Py-GC/MS) was used for the quantification of the aged mulch film residues. Samples were filtered directly into a quartz Fiber filter. Then, filters were cut and inserted directly into the equipment.

Pyrolysis was performed by rapid heating of the sample to 600 °C in an inert atmosphere (He) and the released products were analysed. The pyrolyzer is connected to a gas chromatography/mass spectrometry system. The chromatographic system employs an Ultra Alloy UA+-5 capillary column (30 m × 250 µm × 0.25 µm internal diameter). The oven temperature is held for 2 min at 40 °C, the temperature is increased to 280 °C at a rate of 20 °C/min and held for 10 min, and then increased to 320 °C at a rate of 40 °C/min holding for 15 min.

The identification of the polymers is carried out thanks to the pyrolyzed compounds. This identification is carried out by comparing the mass spectra obtained in the chromatogram and the spectral libraries installed in the analysis equipment. (NIST and F-Search MPs).

Quantification of polymers depends on the characteristic degradation compound used to construct the calibration curve, whether it is above or below the limit of quantification (LOQ) or the limit of detection (LOD). Both limits are reported in Table A1.

2.6. Statistical Analysis

A statistical analysis was performed to evaluate the effect of residues from mulch films on the different bioindicator organisms tested. The analyses were performed using the statistical program R, version 4.5.0 (R Core Team, Vienna, Austria). Prior to performing the ANOVA, the assumptions of normality and homogeneity of variances were verified using the Shapiro–Wilk and Levene tests, respectively, to ensure that the data met the conditions required for the analysis of variance. ANOVA analysis of variance was applied to determine the existence of significant differences between treatments, followed by Tukey's post hoc test for the specific identification of treatments that showed significant differences ($p < 0.05$).

3. Results

3.1. Biological Tests

3.1.1. Growth Rate in Sea Urchin Embryos

The growth results on day 0 (Figure 1a) showed that concentrations of conventional polymer residues above 1000 particles/mL caused slight growth inhibition (around 15% compared to the control). No changes were observed at concentrations of 30 and 300 particles/mL. Larvae treated with biopolymer residue showed no changes in growth compared to the control (Figure 1b).

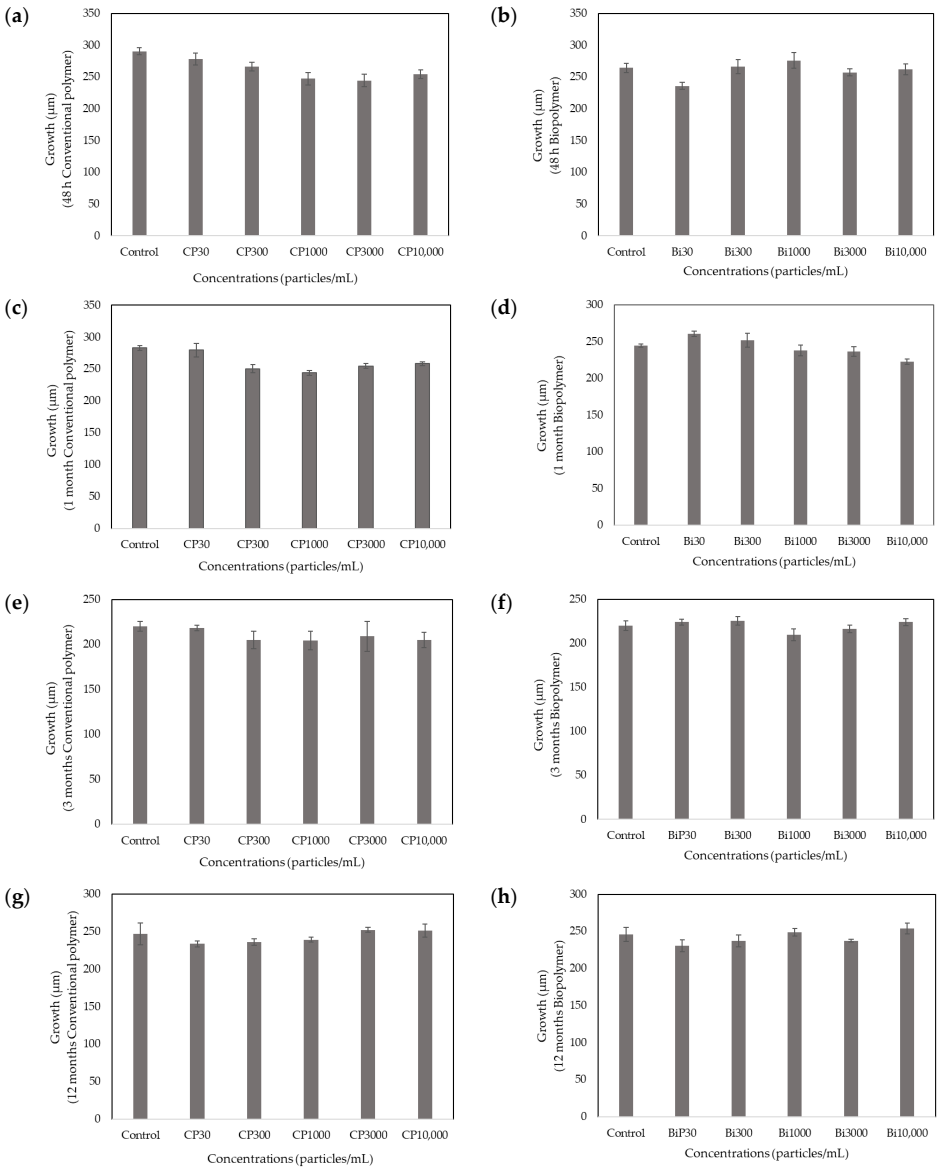


Figure 1. Bar chart showing the growth ratio of *P. lividus* larvae exposed for 48 h to a conventional polymer (CP) and a biopolymer (BI) residue. Growth of larvae exposed to non-aged plastic residue (**a**,**b**); larvae exposed to 1-month-aged plastic residue (**c**,**d**); larvae exposed to 3-month-aged plastic residue (**e**,**f**); larvae exposed to 12-month-aged plastic residue (**g**,**h**). Bars indicate the median values of 4 replicates and error bars the standard error. No significant values ($p > 0.05$) compared to the control treatment (One-Way ANOVA and Tukey test).

After 1 month of aging, conventional polymer residue produced a reduction in sea urchin larvae growth, starting at a concentration of 300 particles/mL (Figure 1c). The concentration of 30 particles/mL did not produce any change in growth compared to

the control. Biopolymer residue did not produce changes in growth at any concentration (Figure 1d). After 3 (Figure 1e,f) and 12 months (Figure 1g,h) of aging, none of the types of mulch film residue analyzed had an effect on growth at any of the concentrations tested.

3.1.2. Germination Rate and Plant Biomass

The samples of conventional polymer residue, analyzed after incubation periods of 0 and 3 months, showed no adverse ecotoxicological effects on the plant species evaluated, as both the germination rate and the biomass of the soil treated with the plastic sample were greater than 90% compared to the control soil, complying with the criteria established in standard EN 17033 (Figure 2).

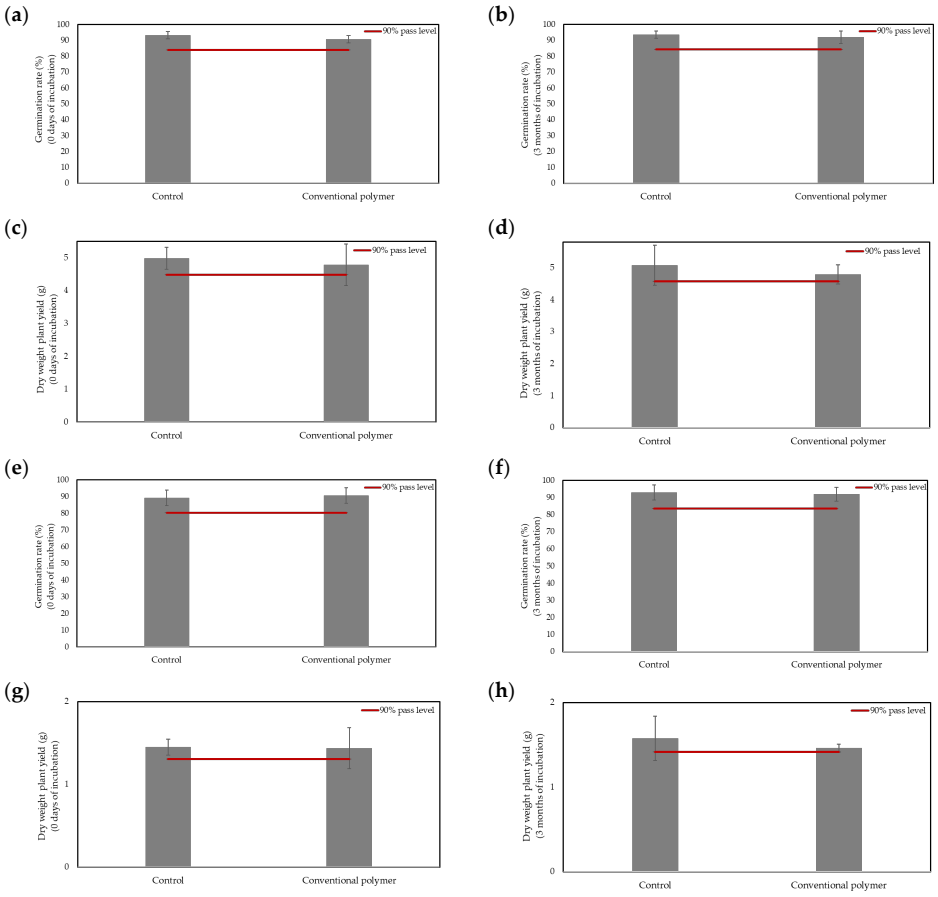


Figure 2. Bar chart showing germination rate (%) and plant yield in dry weight (g) for the different treatments, with conventional polymer residue incubation times of 0 and 3 months, in the higher terrestrial plants analyzed: *Cucurbita maxima* (**a**–**d**) and *Hordeum vulgare* (**e**–**h**). The red line represents 90% of the control. Bars indicate the median values of replicates and error bars the standard error. No significant values ($p > 0.05$) compared to the control treatment (One-Way ANOVA and Tukey test).

The samples of biopolymer residue analyzed after 0 and 3 months of incubation showed no adverse ecotoxicological effects on the evaluated plant species, since both the germination rate and the biomass of the soil treated with the plastic sample were above 90% compared to the control soil, thus meeting the criteria established in the EN 17033 standard (Figure 3).

3.2. Analysis of Aged Mulching Film Residues

The concentration of conventional polymer residues remained essentially constant throughout the natural weathering experiment (Figure 4a), as expected. Samples were

analyzed at time zero, 1 month, 3 months, and 12 months, yielding an average concentration of 1067.96 ± 67.34 µg/L.

In contrast, when evaluating biopolymer residues (Figure 4b), a very low concentration was initially detected at time zero (9.33 ± 2.71 µg/L), with no detectable signal from month 1 onwards. This suggests that the biodegradation process under the tested natural weathering conditions is initiated within the first hours and becomes undetectable within a few weeks.

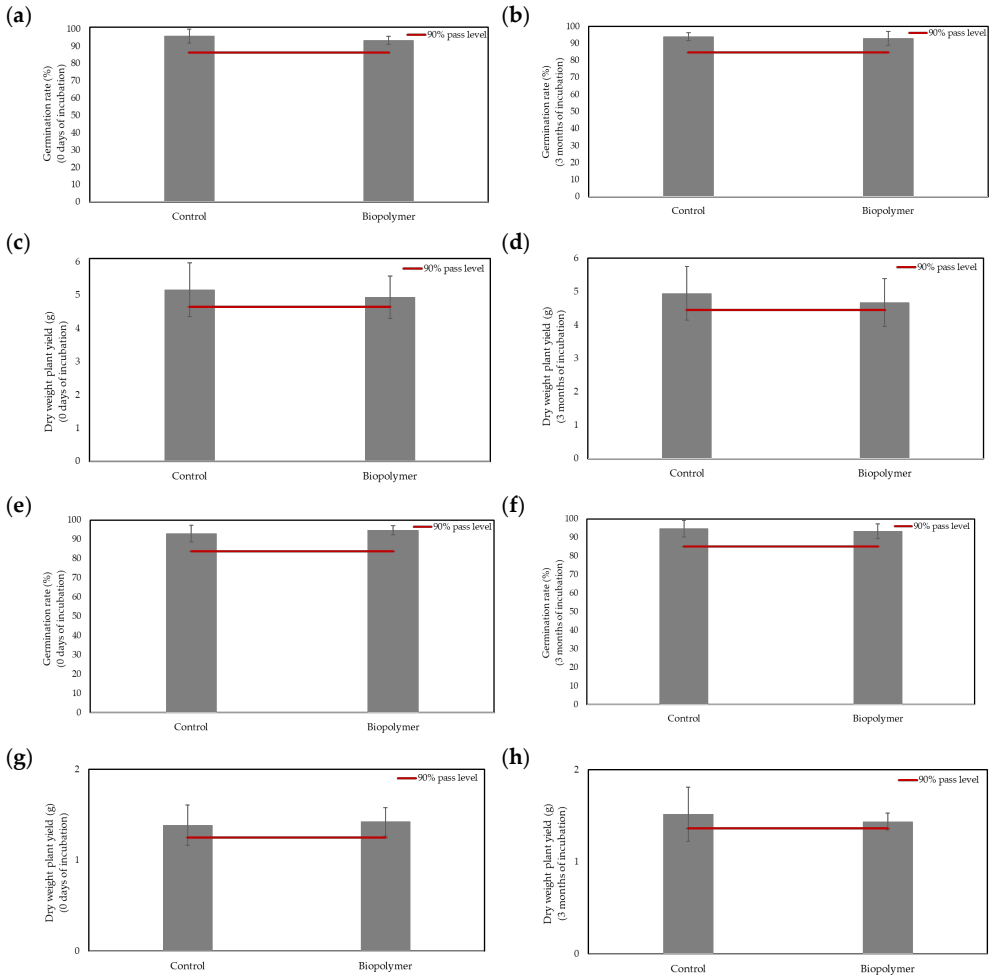


Figure 3. Bar chart of germination rate (%) and plant yield in dry weight (g) for the different treatments at 0 and 3 months of incubation of the biopolymer residue, in the analyzed higher terrestrial plants: *Cucurbita maxima* (**a**–**d**) and *Hordeum vulgare* (**e**–**h**). The red line represents 90% of the control. Bars indicate the median values of replicates and error bars the standard error. No significant values ($p > 0.05$) compared to the control treatment (One-Way ANOVA and Tukey test).

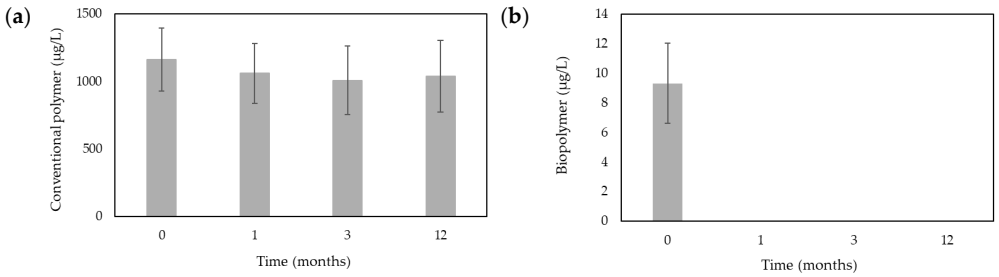


Figure 4. Quantification of aged conventional polymer (**a**) and biopolymer (**b**) residue across 1 year. Samples for analysis were taken in months 0, 1, 3 and 12.

4. Discussion

At an international level, the use of sea urchin embryos is recommended to assess the quality of aquatic ecosystems [32,33]. Conversely, ecotoxicological tests aimed at evaluating soil quality are typically based on the use of higher plant species as biological indicators [34,35].

The Sea Urchin Embryo Test (SET) is a well-established and sensitive bioassay used to evaluate the toxicity of various substances in marine environments. This test employs sea urchin gametes and embryos, which are particularly susceptible to environmental stressors. The SET assesses endpoints such as fertilization rate, embryonic development, and larval malformations. Its popularity stems from the high sensitivity of sea urchin embryos to contaminants, the relatively short duration of the test (48–72 h), and the ecological relevance of sea urchins within marine ecosystems. This bioassay has been successfully applied to assess the toxicity of plastic residues and associated pollutants, providing valuable insights into their potential impact on marine life [36–38].

The results obtained from the SET assays show a significant inhibition of embryolarval growth in *P. lividus* after 48 h of exposure to residues from non-aged conventional polymer at concentrations that could be considered within a medium-to-high environmental range. This is consistent with previous studies that reported reductions in morphometric parameters and an increase in larval malformations in sea urchins exposed to microbeads of conventional polymers [39,40]. After the plastic residues had aged for one month, toxicity was detected even at environmentally relevant concentrations. This effect could be attributed to surface modifications of the polymer, an increase in biofilm coverage, and a greater release of potentially toxic compounds present in the plastics [41,42]. Hu et al. (2023) reported synergistic effects between aged plastic residues and organic pollutants, supporting the hypothesis of increased toxicity in partially degraded polymers [43]. After three and twelve months of aging, the conventional polymer residues lost their apparent toxicity [44], probably due to the partial mineralization of the polymer and the formation of a stable biofilm layer, which reduces direct contact with the plastic surface and moderates the release of toxic substances [45,46].

In contrast, biopolymer residues did not show any adverse effects on larval growth at any of the aging times studied, contradicting previous studies that reported bioplastic toxicity in marine invertebrates [47]. It is possible that the chemical composition and the slower release of additives in these biopolymers reduce their initial impact on early development. This result is consistent with a recent study reporting that most bio-based plastics show measurable toxicity to *P. lividus* larvae linked to residual additives [48], supporting an additive-driven rather than biodegradability-driven explanation for the absence of toxicity observed.

This research highlights the need to consider the environmental aging of plastic residues when assessing ecological risks. Since the highest toxicity is observed at intermediate stages of degradation, we propose that future studies combine larval growth bioassays with analyses of leached substances, biofilm characterization, and morphological measurements. Moreover, assessing combined effects with other stressors, such as heavy metals or organic pollutants, will provide a more comprehensive understanding of the impact of plastic residues on marine biota.

The Terrestrial Higher Plant Test is a standardized and essential tool for assessing the potential ecotoxicological effects of different materials on terrestrial organisms. This assay focuses on representative plant species, both monocotyledons and dicotyledons, which serve as sensitive bioindicators. By measuring parameters such as germination rate and biomass, the test allows the evaluation of the influence of materials on plant development [49,50]. The concentration of the plastic sample analyzed in the present study

was 1%, which is higher than the expected loading for biodegradable films in soil, as specified in the EN 17033 standard. To ensure the absence of toxicity, both germination and biomass must exceed 90% of the control values, according to the criteria established in the standard.

The bioassay results show that exposure to conventional polymer residues did not cause any negative effects on the germination rate or biomass of the plant species evaluated at any of the conditioning times considered, as shown in Figure 2. These results contrast with studies such as that of Qi (2020) [51], in which residues from conventional polymer film induced adverse effects on wheat development, affecting both the aerial parts and the root system of the plants; and with other studies where mulch residues, in macro- and microplastic form, have been associated with biomass reductions and developmental alterations in *Triticum aestivum* in pot experiments [52]. The absence of adverse effects in the present study may be attributed to the fact that, under the applied experimental conditions, the effective exposure of plants to potentially toxic fractions or to effects derived from conventional polymer was insufficient to trigger detectable phytotoxic responses, unlike in other studies where higher residue concentrations and longer exposure times were used.

In the case of the biopolymer, the presence of plastic residues also did not cause any adverse effects on the parameters evaluated in terrestrial plants for any of the conditioning times considered, as shown in Figure 3. These results differ from previous studies [53,54] in which biopolymer residues derived from biodegradable plastic films were associated with growth reductions and physiological alterations in different cultivated species. A possible explanation is that, under the specific conditions of this assay, the changes induced in soil properties did not reach levels sufficient to trigger detectable phytotoxic responses, in line with other studies where certain biopolymers have shown no significant ecotoxicological effects on higher plants [55,56].

In the context of current research, although there is already a solid evidence base regarding the impacts of conventional polymer residues on plant development, studies that comparatively address the effects of biopolymer residues remain relatively limited. This scarcity of research makes it difficult to establish a robust and scientifically well-supported understanding of the ecotoxicological effects associated with biopolymers in soil systems.

The purpose of a biopolymer is to undergo degradation under specific environmental conditions (e.g., soil, freshwater, or marine environments) once its service life has ended. Although the biopolymer evaluated in this study is not intended for marine disposal, the natural weathering assay demonstrated its complete degradation in a marine environment within a few days, as shown in Figure 4.

5. Conclusions

The main findings of this study can be summarized in two key points:

In marine environments, the results of the ecotoxicological tests showed that exposure of *P. lividus* larvae to residues from conventional mulch films caused growth delay when the residues were either non-aged or subjected to aging for only a few months, even at concentrations that could be considered environmentally relevant. In contrast, no growth impairment was observed when larvae were exposed to residues that had undergone prolonged environmental aging. Exposure of larvae to residues from biodegradable mulch films did not produce any effect on growth at any of the concentrations or exposure times tested. In terrestrial environments, the results demonstrated that exposure of *H. vulgare* and *C. moschata* to residues from conventional mulch films did not induce adverse effects. Likewise, exposure to residues from biodegradable mulch films did not result in any negative effects. The findings of this study indicate that residues derived from plastic samples of both conventional and biodegradable mulch films did not elicit relevant ecotoxicologi-

cal effects in the model organisms representative of the two scenarios considered for the end-of-life stage of this plastic product. This pattern was consistent for the material prior to use as well as after biodegradation and natural aging processes. Furthermore, the results underscore the need for long-term studies to identify potential subchronic or chronic effects and to support more comprehensive assessments of the environmental risk associated with the use of these products.

The results of this study demonstrate a clear contrast in environmental persistence between conventional and biodegradable mulch films under marine natural weathering conditions. While conventional polymer residues remained stable over the 12-month period, the biopolymer underwent rapid degradation, becoming undetectable within a short timeframe. These findings highlight the potential of biodegradable materials to significantly reduce long-term plastic accumulation in the environment. However, their performance remains strongly dependent on environmental conditions, underscoring the importance of aligning material design with intended end-of-life scenarios.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

%	Percentage
°C	Degrees Celsius
µL	Microliter
µm	Micrometer
ANOVA	Analysis of Variance
APE	Agriculture Plastic Environment
AVG	Average
BDMs	Biodegradable Plastic Mulches
EN	European Standard
FSW	Filtered Seawater
g	Gram
h	Hour
He	Helium
ISO	International Organization for Standardization
kt	kilotons
L	Liter
LOD	Detection Limit
LOQ	Quantification Limit
m	Meter
mg	Milligram
min	Minutes

mL	Milliliter
OECD	Organisation for Economic Co-operation and Development
PS	Polystyrene
Py-GC/MS	Pyrolysis–Gas Chromatography–Mass Spectrometry
PSU	Practical Salinity Units
SD	Standard Deviation
SET	Sea Urchin Embryo Test
SOC	Soil Organic Carbon
UE	European Union
UV	Ultraviolet
w/*w*	Weight-to-weight

Appendix A

Table A1. Limits of detection (LOD) and quantification (LOQ) for each polymer analyzed.

Polymer	LOD (µg)	LOQ (µg)
Polyethylene (PE)	4.9	16.3
Polypropylene (PP)	1.3	4.3
Polystyrene (PS)	0.4	1.5
Acrylonitrile-butadiene-styrene (ABS)	0.6	1.9
Styrene-butadiene rubber (SBR)	0.6	1.9
Poly(methyl methacrylate) (PMMA)	0.3	0.9
Polycarbonate (PC)	0.2	0.6
Polyvinyl chloride (PVC)	1.6	5.2
Polyurethane (PU)	0.2	0.5
Polyethylene terephthalate (PET)	0.7	2.2
Nylon-6 (N6)	0.2	0.5
Nylon-6,6 (N66)	0.8	2.7

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