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Alternative Mulches for Sustainable Greenhouse Tomato Production

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Abstract: Soil mulching has advantages for horticultural crops, from both agronomic and phytosanitary points of view. The most common material used is polyethylene (PE); however, promising alternatives from the circular economy exist, such as straw (ST) and biodegradable biopolymers (BBs). The effect of the three aforementioned mulches was evaluated and compared to non-mulched soil in a Mediterranean greenhouse for two years of an organic tomato crop. Physical (moisture and temperature) and physicochemical properties of the soil, in addition to crop yield and the effect of the mulches on weed control, were assessed. Additionally, the deterioration of plastic mulches was assessed. The temperature was higher in the mulched soils, but few differences were found between soil and BB at the end of the second cycle. Evaporation was lower in mulched soil, in general, without big differences among the types of mulch. Crop yield did not show differences. At the end of the trials, of the 16 physicochemical variables evaluated, only a slight increase in pH was detected in the ST-mulched plots. BB film degradation reached 5.6% and 6.7% of the total surface at the end of the first and second cycles, respectively. Weeds were equally limited for PE, BB, and ST mulches, but cereal seeds contained within the straw germinated randomly all over the crop cycle. In summary, straw and biodegradable plastic mulches offered the same benefits as conventional PE mulch. Therefore, they can be considered a feasible and more sustainable option, in addition to being consistent with the principles of the bioeconomy.

Keywords: biodegradable biopolymer; mulching; polyethylene film; straw

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1. Introduction

The global demand for plastics and their production has increased in recent decades and is envisaged to further increase in the future, intensifying the impact of plastic on the environment and human health [1]. It is estimated that 79% of plastic waste has ended up in landfills or the natural environment [2]. Thus, the prevention and minimization of waste of petroleum-based plastic materials is currently considered one of the main challenges of today's societies, and reducing plastic pollution has been pushed to the top of the global policy agenda [3]. As an example, in 2018, the European Commission adopted the European Strategy for Plastics in a Circular Economy [4].

Agriculture generates a large amount of plastic waste worldwide, both in open-field and greenhouse production systems. Plastics provide many services in modern agriculture, where they are mostly used in the form of film. Within the Mediterranean basin, in the south-east of Spain, the largest concentration of greenhouses in the world is located; specifically, the Almería greenhouse surface area reached 32,554 ha in 2021 [5]. Plastic used as a protection material by greenhouses in Almería represents approximately 6% of the total volume of waste produced (the remaining 94% is organic residues), and plastic mulch (4900 tons per year) represents 3% of the inorganic waste produced [6]. The current system of external management of plastic waste and by-products does not offer a complete solution to the needs of the sector [7].

Plastic mulch is widely used for intensive vegetable production systems, as it is an effective practice for increasing soil temperature, increasing water use efficiency, decreasing weed growth, and minimizing nutrient lixiviation [8–11]. In addition, the use of plastic mulch is reported to increase energy efficiency in greenhouses with passive air conditioning [12], in addition to being an efficient tool for earlier production and improving fruit yield and quality [13,14]. However, polyethylene, the main material of plastic mulches, is a polluting and poorly degradable material. In addition, for polyethylene mulch film fragments, exposure to sunlight, moisture, and adverse environmental conditions make its complete removal from farmland difficult, leading to a gradual but significant accumulation of microplastics in soils, which negatively impacts soil health and the environment [15–18]. Furthermore, although in many cases the recycling of polyethylene mulch is insufficient, in other cases the presence of highly persistent active compounds from agrochemicals makes the material unattractive for recycling at the end of its useful life [19–21]. For these reasons, polyethylene plastic mulch is a major issue in agriculture [22]. As biodegradable materials do not produce wastes that require disposal, they may represent a sustainable ecological alternative to polyethylene films. Biodegradable plastic mulches (e.g., biopolymers), paper-based mulches, and plant debris (e.g., dried cereals straw) are promising alternatives to alleviate polyethylene plastic mulch pollution [9,11,23]. In addition, at the end of their life, these biodegradable materials can be integrated directly into the soil, where microorganisms transform them into carbon dioxide or methane, water, and biomass, with direct effects on soil properties [9,24,25], making them consistent with the principles of a circular economy.

As there is an urgent need to find alternatives to the use of polyethylene plastic mulch that are sustainable in terms of the environment and human health, and that are viable for use in greenhouse vegetable production systems, it is necessary to study different biodegradable mulches to assess their impact on the main agronomic parameters that have a direct impact on horticultural crops. In this study, the effect of two biodegradable mulches (biodegradable plastic mulch and dried barley straw) was evaluated and compared to polyethylene plastic mulch and non-mulched soil in a Mediterranean greenhouse for two years of growth of an organic tomato crop. The objective was to assess the effect of these mulches on the physical (moisture and temperature) and physicochemical properties of the soil, in addition to crop yield and weed control. Additionally, the deterioration of plastic mulches (polyethylene and biodegradable plastic mulches) was assessed.

2. Materials and Methods

2.1. Location and Experimental Greenhouse

The trials were conducted for two consecutive years (2019/2020 and 2020/2021 seasons) at the Andalusian Institute for Research and Training in Agriculture and Fisheries (IFAPA) in Almería (36°48′ N, 2°41′ W; altitude 142 m), the biggest Mediterranean greenhouse cropping region, and the main organic winter tomato production area in Europe. The local climate is Mediterranean arid, with mild winters and hot, rainless summers. The experimental greenhouse was representative of the "raspa y amagado" Mediterranean greenhouse [26], and has been certified for organic production by the Andalusian Organic Farming Committee (C.A.A.E.) since 2006. The maximum and minimum heights in the greenhouse were 3.9 and 2.3 m, respectively. The greenhouse area was 832 m^2, and it had a west–east orientation, with crops rows aligned north–south. The irrigation system was automated, with droppers located at 0.5 m intervals, and a discharge rate of 3 L h^{-1}. The greenhouse had a 200 μm thick polyethylene cover, with theoretical transmissivity of 90% and thermal properties, and zenithal and lateral ventilation with an anti-aphid mesh (20 × 10 threads/cm^2). Two zenithal windows were east-facing and two west-facing, while the lateral windows were located on all four sides of the greenhouse. Similarly, the lateral and zenithal windows had deflectors in their lower part, which improves air circulation in the area occupied by the crop [27].

2.2. Plant Material and Cropping Details

Two subsequent winter cycles of tomato (*Solanum lycopersicum* L.) "Valenciano type" plants, grafted onto Armstrong® rootstock (Syngenta, Switzerland), were grown in the same greenhouse in the seasons 2019/20 and 2020/21 (i.e., Year 1 and Year 2, respectively). Four-week-old tomato plants were planted on 16 September 2019 and 25 September 2020, in Years 1 and 2, respectively. In both years, prior to planting, in July, fresh sheep manure was buried uniformly throughout the greenhouse at a rate of 4 kg m^{-2}. With the aim of favoring the manure's decomposition, the soil was covered with transparent polyethylene film (30 µm, TIF Desinfección DS®, Sotrafa, Spain) for a period of two months, after a single irrigation application to reach saturation at a 15 cm depth, which is known as the soil biosolarization technique. Planting took place two days after removing the film. Crop growth occurred on two axes, considering each as an individual plant for sampling purposes, thus resulting in an overall density of 2 plants/m^2. Tomato vines were vertically trained with polypropylene strings, and pruned and managed according to established local practices. For correct and optimal pollination, bumblebees *(Bombus terrestris)* were used. Crop management and pest control were guaranteed by adhering to Regulation (EU) 2018/848 on organic production. Irrigation was based on the moisture content of the soil in the reference treatment (–15 to –10 kPa), and a nutrient solution was supplied according to the crop phenological stage and adjusted to the Commission Implementing Regulation (EU) 2021/1165 on products and substances for use in organic production. All experimental plots were fertigated in the same manner in each of the experimental years (see Supplementary Materials Table S1).

2.3. Soil Mulches Materials and Experimental Design

The treatments consisted of different soil mulch materials: (i) dried barley straw applied at 1.21 kg m^{-2}, (ii) black polyethylene film 37.5 µm thick (SOTRAFILM NG, Sotrafa, Spain), (iii) black biodegradable biopolymer plastic film 18 µm thick (SOTRAFILM NG BIO, Sotrafa, Spain), and (iv) non-mulched soil as a control treatment. Each treatment was replicated in three different plots (n = 3), with a randomized complete block design. The factor was the type of mulching (four levels). The 12 experimental plots consisted of 33 m^2 (i.e., 66 plants) (Figure 1). At the end of the crop season in Year 1, the two biodegradable materials (dried barley straw and black biodegradable biopolymer plastic film) were buried to favor their biodegradation.

Figure 1. General view of the experiment at 30 days post planting (Year 1).

2.4. Analyzed Variables

2.4.1. Soil Matric Potential

The soil moisture measurements of the experimental plots were carried out with tensiometers (Irrometer, Riverside, CA, USA) installed at a depth of 15 cm, and located at the same distance from the plants and the irrigation emitters (15 cm). The readings were carried out daily and at the same time in the morning, just before watering. The results corresponded to the weekly average measurements in kPa. Additionally, two tensiometers were installed at a depth of 30 cm in the non-mulched soil experimental plots in order to avoid infiltration or excess irrigation.

2.4.2. Soil Temperature

For the measurement of soil temperature, each experimental plot had thermistor type sensors, model WAM-200TS-15, which recorded data at intervals of 30 min, and were stored in a WATERMARK Monitor 900 M datalogger of IRROMETER with capacity for eight sensors, powered by a 9 volt battery with an output voltage of 0–5 V and 4–20 mA, and with a storage capacity of 85 days. The results are presented as Monthly and Total Growing Degree-Days Accumulation in the two crop seasons.

2.4.3. Physical and Chemical Variables of Soil Samples

To assess the starting situation, soil sampling was carried out in three areas of the greenhouse immediately before placing the mulches and planting the tomato seedlings. Thus, the soil samples were taken after the biosolarization treatment with fresh sheep manure, three days before planting. Similarly, in both years, at the end of the tomato crop season, all the experimental plots were sampled. The samples were taken with an auger at a depth of 0–30 cm. Three subsamples were randomly taken from cultivation lines and then mixed and homogenized to ensure representativeness in each sample. Subsamples were taken in the center of the cultivation lines to avoid a possible edge effect. Soil samples were then analyzed for pH, electrical conductivity (EC), interchangeable cations (Ca^{2+}; Na^{+}; Mg^{2+}, K^{+}), active limestone, phosphorus Olsen (P Olsen), nitric nitrogen, organic matter, total carbonates (HCO_3^{-}), total nitrogen, C/N ratio, and texture (% of sand, silt, and clay), following standard soil testing procedures as described in Order 5/12/1975 [28] by an external laboratory (Eurofins, El Ejido, Spain). The results of most physical and chemical variables of soil samples are reported in different units for Years 1 and 2. Comparisons among the treatments were made for each year separately.

2.4.4. Crop Yield

The production and yield were measured for all the harvests. In Year 1, the first harvest was undertaken on 27 December 2019 (102 Days After Planting: DAP) and the last on 25 March 2020 (191 DAP). In Year 2, the first harvest was on 30 December 2020 (110 DAP) and the last on 13 April 2021 (200 DAP). In total, 14 harvests were undertaken in both years. The cumulative tomato production was measured (kg m^{-2}) using an electronic balance with an accuracy of $\pm$ 0.01 kg, and the number of fruits per m^2 was recorded.

2.4.5. Weed Assessments

The suppression of weeds was evaluated throughout the two crop seasons. Weed presence was assessed 11 and 9 times in Year 1 and Year 2, respectively. The presence of weeds was assessed in the root zone of all plants in the experimental plots, considering presence or absence regardless of the number of weeds. Weeds were only removed after each assessment. The root zone of each tomato plant was considered a sampling point. Results are expressed as a percentage of weed presence over the total number of sampling points.

2.4.6. Plastic Mulch Deterioration (Polyethylene and Biodegradable Films)

The percent visual deterioration (PVD) of the plastic mulches was evaluated at the end of the crop season in Year 1, and four times throughout the crop season, including at the end, in Year 2. For this purpose, a metal ring of known area (1 m^2) was randomly thrown onto three different places of each experimental plot with plastic mulch treatments (low density polyethylene film and biodegradable biopolymer film). The surfaces occupied by the ring were photographed and subsequently processed with the free software ImageJ 1.52a (NIH Image, Bethesda, MD, USA) to obtain the deteriorated area (perforations and/or breaks). The PVD was calculated as the percentage of soil exposed within the evaluated area, such that 0% represented intact mulch and 100% represented completely deteriorated mulch [29–31].

2.5. Statistical Analysis

Analysis of variance (one-way ANOVA) was used to compare differences among treatments (four levels: dried barley straw, black low density polyethylene film, black biodegradable biopolymer plastic film, and no-mulch control) for each of the variables evaluated in the study (soil matric potential, soil temperature, physical and chemical variables of soil, crop yield, weed control, and plastic mulch deterioration) for both years. Previously, normality and homoscedasticity were tested using the Shapiro–Wilk and Levene tests, respectively. For these analyses, Fisher's least significant difference (LSD) test was used to make comparisons of treatments of the most interest, using the 5% level of significance. Arcsine square root transformation was applied to percentages before analyses. The statistical analyses were carried out using the statistical software package Statgraphics Centurion XVIII (Statgraphics Technologies, Inc., The Plains, VA, USA) for Windows (Microsoft Corporation, WA, USA).

3. Results and Discussion

3.1. Soil Matric Potential

The reduction in water loss by mulch is a positive feature of its use, especially because it allows for longer irrigation intervals and water saving [32]. The effect of the assessed mulches on soil moisture was very similar throughout the tomato crop season in Year 1. In general, during the first crop season (Year 1), the non-mulched soil showed lower moisture than the mulched soils, although significant differences in soil matric potential values ($p < 0.05$) between mulches and the non-mulched soil were only detected at the beginning of the crop season, mainly due to the high dispersion of the values in the non-mulched experimental plots (Figure 2, Year 1). The soil moisture in the plots with polyethylene mulch seemed to be higher than that of the other mulches in the final four weeks of the crop season in Year 1, but no significant differences were detected ($p > 0.05$). Throughout the second year, the effect of soil mulches on soil moisture was similar to that in the first year, showing significant differences in soil matric potential values between the mulches and non-mulched soil only at three time points (Figure 2, Year 2). These results suggest that straw acts efficiently in maintaining soil moisture. In this regard, Cirujeda et al. [33] reported similar effects, which may be due to some extent to the decrease in radiant energy absorbed by the soil [34]. However, Lei et al. [35] concluded that plastic mulches conserve soil moisture more efficiently than vegetable mulches (e.g., straw), as plastic mulches are more impermeable to water vapor than vegetable mulches. In addition, the use of polyethylene plastic mulch is reported to achieve the greatest effects in terms of water economy, as its high impermeability prevents evaporation from the soil surface, leaving water available to the crop, which benefits from a more constant and regular supply [36–39]. On the contrary, Yang et al. [40] and Ghosh et al. [41] concluded that straw mulches maintain a higher soil water content than plastic mulch and bare soil. By comparison, the progressive deterioration of biodegradable mulches reported throughout the crop season (see Section 3.6) did not lead to lower soil moisture.

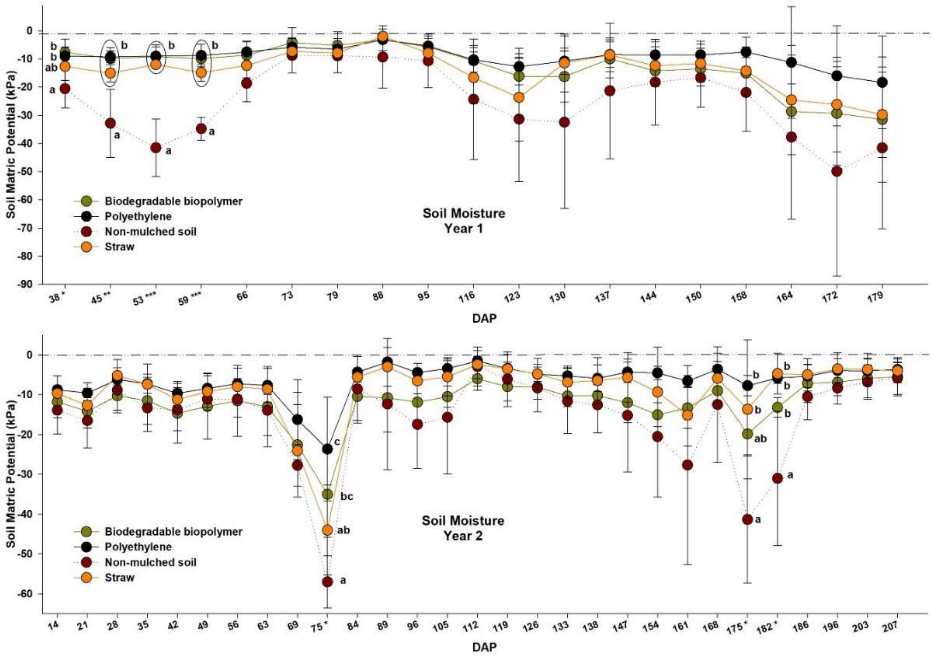

Figure 2. Soil matric potential (kPa) during the two crop seasons (weekly averages) depending on mulch type and in non-mulched soil. Values (mean ± standard deviation; $n = 3$). Different letters in the same week indicate significant differences ($p \leq 0.05$, Fisher's LSD test). '*', '**', and '***' indicate significance at $p \leq 0.05$, 0.01, and 0.001, respectively. DAP: Days After Planting.

3.2. Soil Temperature

For a better understanding of the results, it should be noted that the crop cycle was longer in the second year of the study. Crop cycles ended on 25th March and 13rd April in the first and second years, respectively. Moreover, the climate conditions were different in both years; these are the reasons for the differences found between the two years.

In the first year, Total Growing Degree-Days Accumulation for the whole crop season showed a significant increase ($p < 0.05$) when soil mulches were used compared to non-mulched soil, whereas no differences ($p > 0.05$) were detected among soil mulches (Figure 3, Year 1). Total Growing Degree-Days Accumulation for the whole crop season were 1406, 1324, 1297, and 1096 for polyethylene, biodegradable biopolymer, straw, and non-mulched soil, respectively. In general, the same trend was observed from October to January (included) when results were considered as the Monthly Growing Degree-Days Accumulation. However, values in February and March were higher in the soil with polyethylene mulch (205 and 217, respectively) compared to the rest of the treatments, whereas biodegradable mulches (183 in February and 200 in March) and straw (175 in February and 176 in March) did not show differences compared to non-mulched soil (155 in February and 196 in March).

In the second year, the Total Growing Degree-Days Accumulation for the whole crop season showed a significant increase when polyethylene mulch was used compared to non-mulched soil, and to straw and biodegradable mulches. Total Growing Degree-Days Accumulation for the whole crop season were 1677, 1558, 1580, and 1479 for polyethylene, biodegradable biopolymer, straw, and non-mulched soil, respectively. In this case, soil temperature was higher in the plots with straw mulch compared to with non-mulched soil, whereas no differences were detected when biodegradable mulch was used (Figure 3, Year 2). Similarly, generally the same trend was observed from October to April when the Monthly Growing Degree-Days Accumulation was considered, although it must be highlighted that there were no differences among treatments in February. In addition, in April, when air temperature in the greenhouse was higher than the rest of the season, the Monthly Growing Degree-Days Accumulation was lower for the straw mulch (149) compared to the polyethylene and biodegradable plastic mulches (173 and 164, respectively), and even the non-mulched soil (157), which may be beneficial in hot climates. These results agree with Duppong et al. [42] and Kosterna [43], who showed that the use of organic mulches is a feasible way to decrease soil heating in summer and helps to reduce soil temperature fluctuations. Stinson et al. [44] also indicated that organic mulching keeps the soil temperature lower in summer and higher in winter. Moreover, in an open field tomato crop study performed in central Spain, the temperatures reached under polyethylene films were always higher than those for biodegradable films; this may be a disadvantage in hot climates, although it can also be advantageous in colder conditions [45]. In this regard, a large meta-analysis comparing the performance of polyethylene and biodegradable mulch films in annual crops revealed that biodegradable mulch reduced soil temperature by 4.5% compared with polyethylene mulch [46]. Our results showed the efficacy of mulches to increase soil temperature in different periods throughout the winter crop season, even in colder months when this increase can be more beneficial. In this regard, López-Marín et al. [14] stated that one of the greatest benefits of plastic mulch is the increase in soil temperature, a benefit that is also achieved by dry barley straw mulches [33]. This effect allows crops to develop and reach acceptable yields in cold periods of the year, or in areas with minimum temperatures below the physiological optimum for the cultivated species. In the case of tomato crops, environmental temperatures below 10 °C or over 30 °C cause the plant to stop growing and developing, and the soil temperature becomes limiting when it drops below 12 °C or exceeds 34 °C [47,48]. In this regard, all treatments of this study, including the non-mulched soil, maintained the temperature above the base temperature for tomato growth (Table S2).

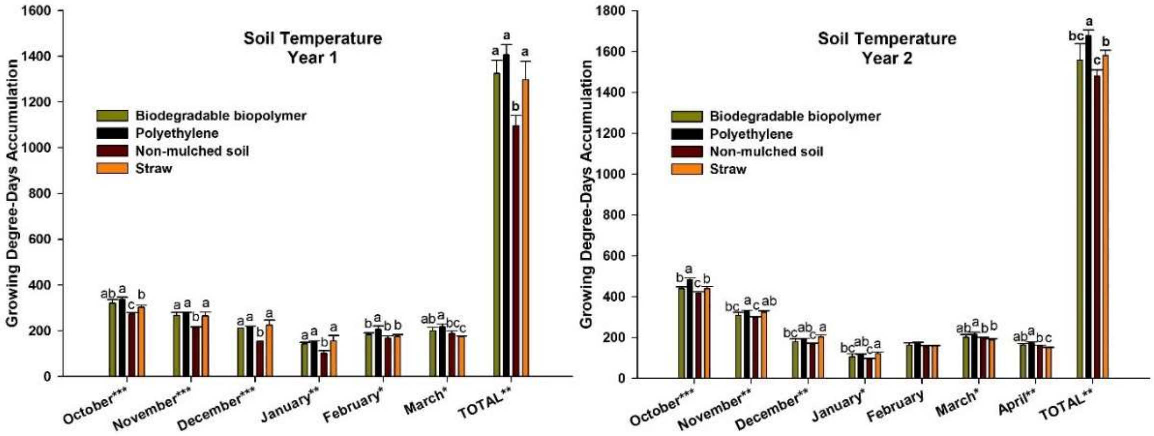

Figure 3. Monthly and Total Growing Degree-Days Accumulation in the two crop seasons depending on mulch type and for non-mulched soil. Values (mean ± standard deviation; n = 3). Different letters in the same period indicate significant differences ($p \leq 0.05$, Fisher´s LSD test). '*', '**', and '***' indicate significance at $p \leq 0.05$, 0.01, and 0.001, respectively.

3.3. Physical and Chemical Variables of Soil Samples

At the end of the first crop season, only the K^+ concentration showed significant differences (p = 0.027) between polyethylene plastic mulch and non-mulched soil, which showed average values of 3391 ± 532 and 1982 ± 303, respectively (Table 1). The increase in K^+ content may be because the process of mineralization of sheep manure incorporated through soil biosolarization occurred faster in soils with polyethylene mulch. Li et al. [49] concluded that there is a greater availability of nutrients in mulched soils, due to the greater microbiological activity caused by the increase in temperature, humidity, and oxygenation in the soil; these parameters directly affect the processes of nitrification and mineralization. In contrast, Moreno and Moreno [45] concluded that the use of polyethylene films resulted in lower values of soil organic matter mineralization, probably due to the increase in the temperature under polyethylene mulch. This disparity of results suggests that the effects of temperature increase on the soil chemical parameters when polyethylene plastic mulch is used depend, to a large extent, on the environmental conditions of the study area.

Table 1. Soil physical and chemical variables at the beginning of the study (start of season 1), and at the end of the two crop seasons, depending on the mulches and for the non-mulched soil.

Soil Physical and Chemical Variables	Start Season 1	End Season 1					Soil Physical and Chemical Variables	End Season 2				
		Straw	Polyethylene	Biopolymer	Non-mulched	*p*-Value		Straw	Polyethylene	Biopolymer	Non-mulched	*p*-value
pH	8.6 ± 0.2	8.1 ± 0.1	8.1 ± 0.1	8.1 ± 0.1	8.1 ± 0.1	0.821	pH (Extract 1:2:5 H_2O)	9.2 ± 0.1a	9.0 ± 0.1b	9.0 ± 0.1b	9.0 ± 0.1b	0.024
CE (dS/m) *	6.19 ± 3.99	2.58 ± 0.44	2.46 ± 0.62	2.28 ± 0.74	3.37 ± 0.74	0.251	CE (dS/m) **	0.53 ± 0.10	0.48 ± 0.04	0.69 ± 0.08	0.81 ± 0.34	0.182
Ca^{+2} (mg/L)	1253 ± 117	5001 ± 1257	5898 ± 869	5563 ± 849	2927 ± 1756	0.071	Ca^{+2} (mg/kg sms)	5753 ± 81	5761 ± 31	5649 ± 144	5678 ± 221	0.706
Na^{+1} (mg/L)	37 ± 8	47 ± 5	51 ± 18	47 ± 10	52 ± 13	0.926	Na^{+1} (mg/kg sms)	218 ± 47	201 ± 24	252 ± 35	304 ± 123	0.348
Mg^{+2} (mg/L)	261 ± 13	383 ± 94	413 ± 8	337 ± 66	314 ± 52	0.292	Mg^{+2} (mg/kg sms)	348 ± 31	339 ± 30	333 ± 16	384 ± 46	0.288
K^{+1} (mg/L)	1841 ± 922	2796 ± 176ab	3391 ± 532a	2573 ± 604ab	1982 ± 303b	0.027	K^{+1} (mg/kg sms)	884 ± 144	819 ± 62	824 ± 105	1009 ± 236	0.431
Active limestone (%)	5.7 ± 1.9	6.0 ± 1.8	4.5 ± 1.7	5.8 ± 2.9	6.3 ± 1.6	0.722	Active limestone (% sms)	7.7 ± 0.6	7.7 ± 0.6	7.7 ± 0.6	7.7 ± 0.6	1.000
P Olsen (meq/L)	19 ± 1	8 ± 1	9 ± 2	8 ± 2	9 ± 1	0.696	P Olsen (mg/kg sms)	61.9 ± 8.3	59.6 ± 8.6	65.0 ± 16.7	67,5 ± 6.6	0.817
Nitric N (mg/L)	157 ± 86	61 ± 23	48 ± 4	52 ± 24	62 ± 25	0.821	Nitric N (mg/kg sms)	7.1 ± 0.9	7.8 ± 5.4	19.0 ± 6.1	21.6 ± 17.8	0.232
Organic Matter (%)	1.2 ± 0.5	1.1 ± 0.0	0.9 ± 0.0	1.1 ± 0.1	1.0 ± 0.2	0.304	Organic Matter (% sms))	2.1 ± 0.1	2.4 ± 0.6	2.1 ± 0.2	2.3 ± 0.2	0.563
Total carbonates (%)	14 ± 4	19 ± 4	18 ± 3	17 ± 5	21 ± 6	0.728	$CaCO_3$ equivalent (% sms)	25.7 ± 1.5	25.0 ± 1.0	26.7 ± 1.2	25.7 ± 0.6	0.394
Total N (%)	0.043 ± 0.015	0.050 ± 0.010	0.040 ± 0.010	0.043 ± 0.006	0.037 ± 0.006	0.297	Total N (% sms)	0.177 ± 0.015	0.180 ± 0.036	0.180 ± 0.036	0.177 ± 0.006	0.999
C/N	20 ± 11	16 ± 4	16 ± 5	17 ± 3	20 ± 2	0.531	C/N	7.02 ± 0.77	7.83 ± 0.68	6.84 ± 0.70	7.47 ± 0.30	0.297
Sand %	68 ± 4	56 ± 3	59 ± 8	59 ± 4	60 ± 7	0.873	Sand %	58 ± 3	57 ± 3	59 ± 2	55 ± 5	0.464
Silt %	13 ± 1	21 ± 4	17 ± 6	20 ± 2	19 ± 6	0.867	Silt %	21 ± 2	22 ± 1	20 ± 1	21 ± 2	0.767
Clay %	19 ± 3	23 ± 1	24 ± 3	21 ± 2	21 ± 1	0.284	Clay %	21 ± 1	22 ± 2	21 ± 1	24 ± 3	0.280

* Results in saturated extract at 25 °C. ** Results in extract 1:5 H_2O at 25 °C.

At the end of the second year, there was only a significant difference in soil pH, which was slightly higher in the straw mulch (pH = 9.2 ± 0.1) treatment compared to the rest of the treatments, which showed the same values (pH = 9.0 ± 0.1; Table 1). However, a decrease in soil pH has been reported when straw is incorporated into the soil [50,51].

Additionally, it should be considered that both straw and biodegradable plastic mulches can be mechanically incorporated into the soil at the end of the crop season, thus avoiding the costs of removal from the field [31] and facilitating the reutilization of plant debris as an organic amendment for the improvement of greenhouse soil fertility [7,52], which is a valuable management technique within the framework of a circular economy. Biodegradable materials have the capacity to disintegrate, fragment, and degrade through the action of microorganisms [24,25]. In this sense, there is a need to carry out residuality studies derived from their decomposition, and, among other aspects, to know the effects that these can have on root growth and plant stress [19]. On the contrary, the incorporation of polyethylene plastic mulch into the soil can have a serious negative impact on the environment as a consequence of its poor final disposal [17,53], due mainly to large accumulations of microplastics from the deterioration of the polyethylene [18]. Therefore, recent studies have aimed to increase knowledge of the advantages and disadvantages of different alternatives to polyethylene plastic mulch on different soil parameters [21,23,54–56].

3.4. Crop Yield

In both years, soil mulches did not significantly influence the early tomato production, based on the production obtained in the first harvest, nor the cumulative total production throughout the crop cycle, nor that at the end of it (Figure 4). No significant differences were detected among mulched plots and non-mulched soil, nor among mulches. In all cases, total tomato production was within the range of common yields for this type of tomato in organic production, and ranged from 11.89 to 12.73 kg m^{-2} and 14.06 to 15.09 kg m^{-2} in Years 1 and 2, respectively.

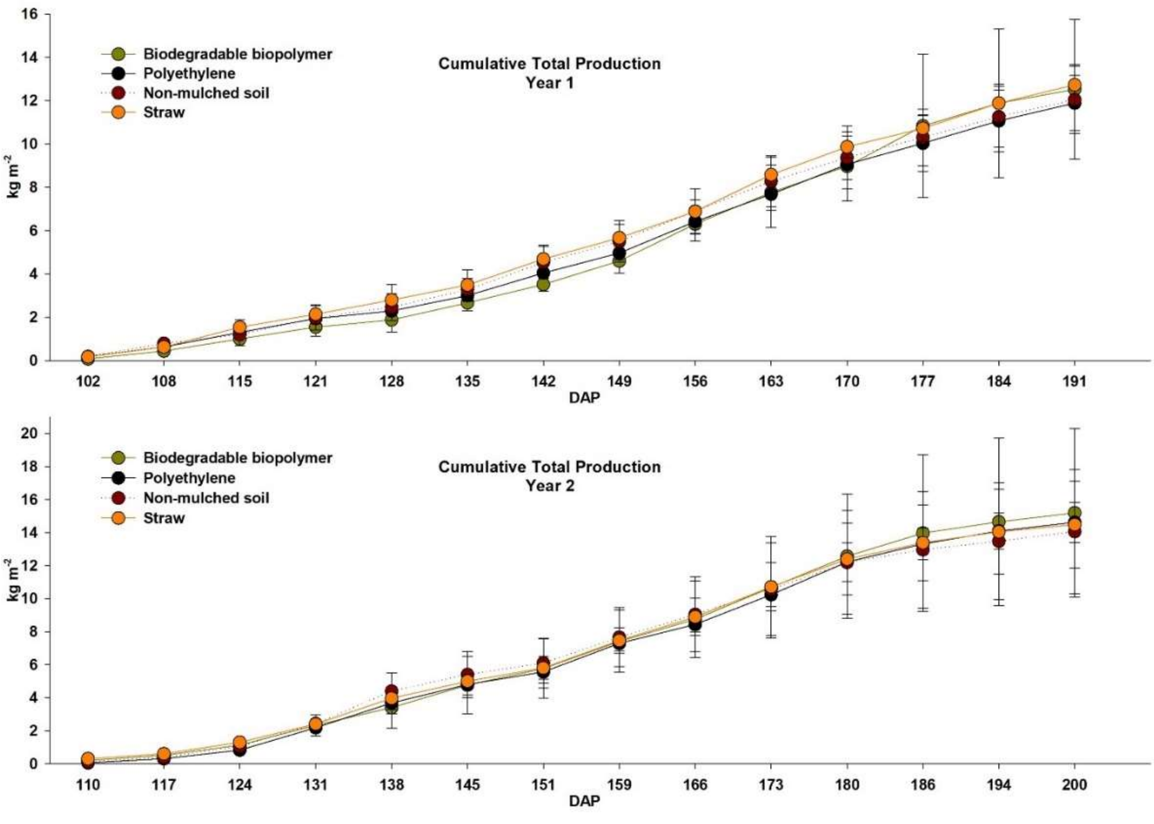

Figure 4. Cumulative tomato production in the two years of study depending on mulch type and for non-mulched soil. Values (mean ± standard deviation; *n* = 3). DAP: Days After Planting.

Similarly, soil mulch did not significantly influence the number of fruits per m^2, with average values ranging from 36.1 to 39.6 fruits m^{-2} and 52.2 to 57.4 fruits m^{-2} in Years 1 and 2, respectively (Figure 5). In this regard, it should be noted that the differences in production and number of fruits between the two years of study (higher values in the second year in both cases) may be mainly due to the fact that in the second year the crop cycle was longer.

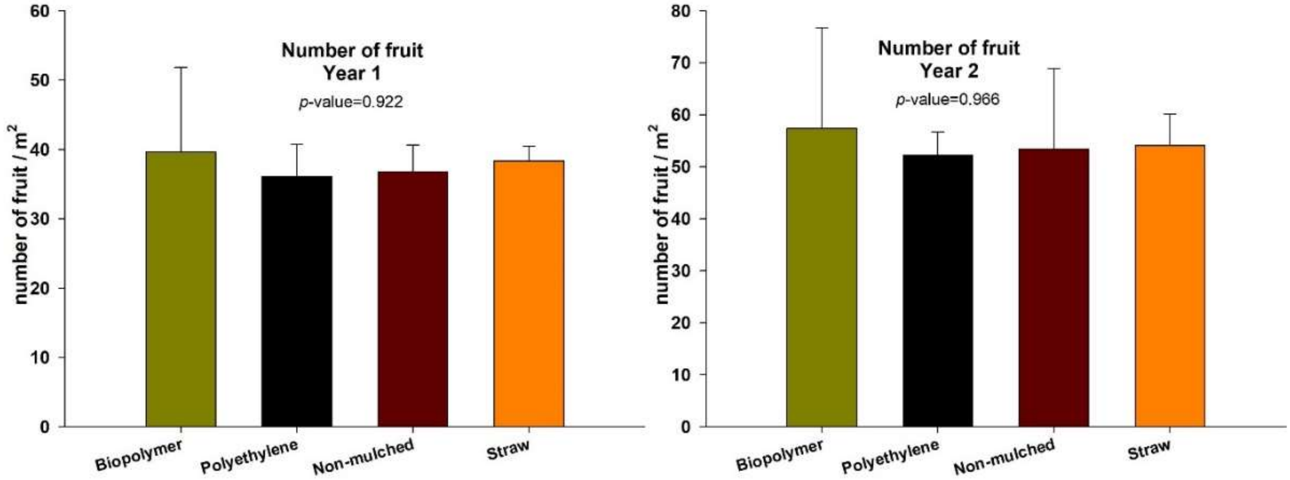

Figure 5. Number of tomato fruits per m^2 at the end of the two crop seasons depending on mulches type and non-mulched soil. Values (mean ± standard deviation; n = 3).

Several authors have concluded that the greater precocity of production in tomato cultivation is one of the most attractive benefits of using soil mulches [48]. In addition, tomato yield (total and marketable production and fruit number) is reported to increase when using polyethylene or biodegradable film mulches compared to non-mulched soil, in both high tunnel and open field production systems [13]. However, tomato yield increases due to soil mulch are not always reported, since yield beneficial effects depend on both the type of film and the geographic location [29]. As a complement, a study performed in central Spain to evaluate the incidence of polyethylene and biodegradable plastic mulches on open field tomato crops concluded that the variability of the yield depended mainly on the number of fruits; the average weight of the fruits was practically constant in the different treatments and seasons, which suggests a strong seasonal and varietal character of this parameter [45]. In this regard, although, under the specific experimental conditions of the present study, there were no positive influences on tomato yield due to the use of mulching, it should be noted that all mulches increased the temperature of the soil with respect to non-mulched soil, while causing a smaller loss in soil moisture, which may allow water savings without negatively affecting crop yield. Similarly, these results differed from those obtained by Nachimuthu et al. [57], who reported lower crop yields of zucchini, pumpkin, and pepper in an open field when plant mulches (e.g., straw) were used compared to plastic mulches.

3.5. Weed Control

Figure 6 shows the average percentages of weed presence depending on soil mulch and for non-mulched soil. Generally, the presence of weeds in non-mulched soil was low and showed no difference to that of plastic mulches (polyethylene and biodegradable biopolymer). The implementation of soil biosolarization treatments could have played a role, as they are considered a viable technique for weed control [58]. Plastic mulches suppressed weeds similarly throughout the crop, without an increase in the presence of weeds due to perforations and deterioration, in any of the cases. These results are in line with those obtained by Minuto et al. [59], who reported no significant difference in weed suppression between polyethylene and biodegradable mulch films throughout the tomato crop season in Italy. Weed growth under plastic mulches is highly dependent on light transmission, especially in the PAR band (400–700 nm) [60], and this is the main reason why Cowan et al. [13] concluded that black and brown biodegradable mulches, but not white, control weeds comparably to black polyethylene mulch in high tunnel tomato production, as was the case in our results. However, it should also be noted that biodegradable plastic films and polyethylene are not always the most efficient option for weed control, as some species (e.g., *Cyperus rotundus* L.) are able to pierce the material [61]. On the other hand, in both years of our study, throughout the tomato crop cycle, the experimental plots with straw mulches reported significantly ($p < 0.05$) greater weed presence than plastic mulches (polyethylene and biodegradable). In addition, the presence of weeds was also higher ($p < 0.05$) in most of the samples when using straw mulch compared to non-mulched soil. The main reason for these differences was related to the germination of barley seeds present in the dried straw used as mulch, since this was the predominant plant species in the experimental plots with this mulch (data not shown). Several studies achieved this result when using cereal straw mulches [33,62,63]. In addition, a recent three-year study [64], in which the assessment of weed presence did not include cereals as weeds, reported similar weed control efficacy when straw mulches (i.e., wheat, barley, and rice straw) were used compared to black polyethylene plastic mulch.

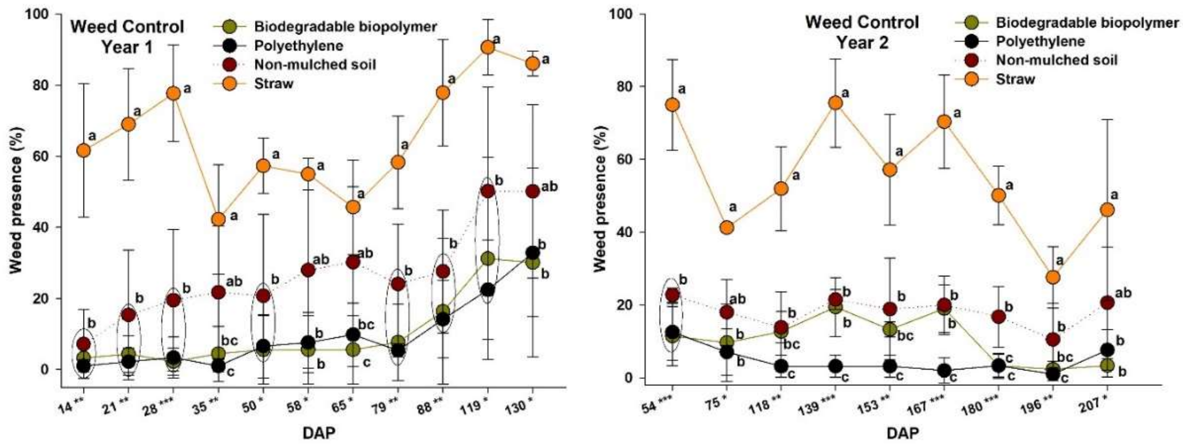

Figure 6. Weed presence during the two crop seasons depending on mulch type and for non-mulched soil. Values (mean ± standard deviation; $n = 3$). Different letters in the same week indicate significant differences ($p \leq 0.05$, Fisher´s LSD test). '*', '**', and '***' indicate significance at $p \leq 0.05$, 0.01, and 0.001, respectively. DAP: Days After Planting.

Soil mulches must suppress the presence of weeds, as in organic production this is considered one of the most complex problems to solve. It is therefore of great interest to study the effects of barley plants on the main crop, to determine whether the competition for water and nutrients that could negatively affect main crop development occurs. If so, additional efforts towards its removal should be considered. However, it may have benefits for soil fertility and/or as a reservoir plant for beneficial insects, among others.

3.6. Deterioration of Plastic Mulches (Biodegradable Biopolymer and Polyethylene)

Figure 7 represents the visual deterioration of plastic mulches (polyethylene and biodegradable biopolymer) at the end of the tomato crop cycle and for the Year 2 cycle, referring to the percentage of deterioration over the total area evaluated. It should be noted that, although mulch visual deterioration assessments (PVD) are generally related to changes in certain mechanical properties of the mulch (e.g., resistance and elongation percentage at break point) [65,66], visual assessment and mechanical properties provide different information on deterioration. In the present study, at the end of the tomato crop season, the visual deterioration of the biodegradable mulch was significantly higher ($p < 0.05$) compared to polyethylene mulch in both years, reaching average values in biodegradable mulch of 6.70% and 5.61% in Years 1 and 2, respectively, compared to 0.98% and 0.02% for polyethylene mulch (Figure 8). In the second year, significant differences were detected from 161 DAP.

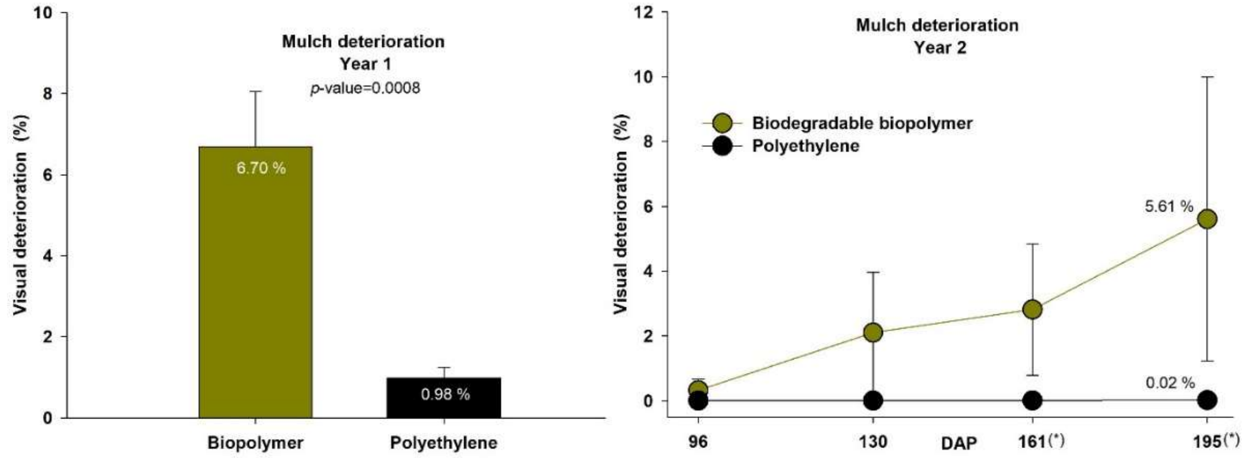

Figure 7. Visual deterioration of plastic mulches (biodegradable biopolymer and polyethylene) at the end of the crop season in Year 1 of the study, and during the crop season in Year 2. Values (mean ± standard deviation; *n* = 3). '*' indicates significance at $p \leq 0.05$ (*t*-Student test). DAP: Days After Planting.

Figure 8. Visual deterioration of biodegradable biopolymer ((**left**); deteriorated area in yellow color) and polyethylene ((**right**); deteriorated area in red color) plastic mulches at the end of the crop season in Year 2 (195 days after planting). Surfaces occupied by the ring (1 m^2) were processed with software to obtain the deteriorated area (perforations and/or breaks).

The higher deterioration of biodegradable plastic mulches compared to polyethylene plastic mulches has been reported by several authors. A two-year study in central Spain reported that polyethylene mulches remained practically intact throughout the open field tomato crop season, while signs of biodegradable mulch degradation appeared from the beginning of its use. However, in general, biodegradable mulches remained functional during use and the deterioration did not affect yield or fruit quality attributes (total soluble solids, firmness, dry weight, juice content, and shape) [45]. Othman and Leskovar [31] reported, in an open field watermelon crop season, that the PVD rates of degradable mulches were 7%, 20%, 37%, 44%, 57%, 83%, and 92% after 120, 180, 210, 240, 300, 330, and 365 d after field transplanting, respectively, while no deterioration was noted in the polyethylene mulch for the same period. Similarly, assessments in three tomato production regions in North America, both in high tunnels and open fields, concluded the greatest PVD was obtained for two commercially advertised black biodegradable plastic mulches, while the values were insignificant for black polyethylene plastic mulch [29]. The same study suggested that overhead moisture may play a larger role than temperature or incident radiation in the deterioration of these mulch products. The high molecular weight and hydrophobicity of polyethylene films lend these films high chemical stability and thus resistance to degradation, requiring about 100 years for its complete decomposition [67,68].

In contrast to the study by Moreno and Moreno [45], in which the biodegradable films, previously buried at the end of the crop cycles, were not visible during the spring following each crop season, in our study biodegradable film fragments in the soil were clearly visible at the end of the second year.

4. Conclusions

From an agronomic perspective, dry barley straw mulch and biodegradable plastic mulch offered the same benefits as the polyethylene plastic mulch in a Mediterranean organic greenhouse winter tomato crop. However, the germination of the numerous cereal seeds present in the dry straw suggests the need to develop further studies in order to understand the possible advantages and/or disadvantages that the grown cereals may have on the profitability of the agrosystem as a whole. Their use in agrosystems is a viable and sustainable option in accordance with the principles of the circular economy and agroecology. Similarly, as these are biodegradable materials that can be incorporated into the soil, their implementation facilitates practices aimed at reducing waste from the farm, such as the reuse of plant debris at the end of the season as an organic amendment for the improvement of soil health and fertility. This avoids the labor and environmental costs associated with the removal and disposal of polyethylene plastic mulch, a material that has a long-lasting negative impact on natural systems. Its promotion and facilitation for the farmer would favor its implementation in intensive greenhouse horticultural production systems, thus complying with Sustainable Development Goals, which are firmly committed to the framework of a circular economy within agricultural systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12061333/s1, Table S1. Fertilizer and water consumption for the two tomato crop cycles corresponding to the two years of the study.; Table S2. Monthly temperature average (Taver), maximum (Tmax) and minimum (Tmin) (°C) for the two years of the study depending on mulches type and non-mulched soil.

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Data Availability Statement: The data presented in this study are available within the article and supplementary material.

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