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Assessment of Yield and Quality of Eggplant (*Solanum melongena* L.) Fruits Improved by Biodegradable Mulching Film in Two Different Regions of Southern Italy

Giuseppe Di Miceli [1], Nicolò Iacuzzi [1,*], Claudio Leto [1,2], Eugenio Cozzolino [3], Ida Di Mola [4], Lucia Ottaiano [4], Mauro Mori [4] and Salvatore La Bella [1]

[1] Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze 13, Building 4, 90128 Palermo, Italy; giuseppe.dimiceli@unipa.it (G.D.M.); claudio.leto@unipa.it (C.L.); salvatore.labella@unipa.it (S.L.B.)
[2] Research Consortium for the Development of Innovative Agro-Environmental Systems (CoRiSSIA), Via della Libertà 203, 90143 Palermo, Italy
[3] Council for Agricultural Research and Economics (CREA)—Research Center for Cereal and Industrial Crops, 81100 Caserta, Italy; eugenio.cozzolino@crea.gov.it
[4] Department of Agricultural Sciences, University of Naples Federico II, 80055 Portici, Italy; ida.dimola@unina.it (I.D.M.); lucia.ottaiano@unina.it (L.O.); mori@unina.it (M.M.)
* Correspondence: nicolo.iacuzzi@unipa.it; Tel.: +39-3289219904

Abstract: Low-density polyethylene (LDPE) mulching films have an important function in crop cultivation; at the end of their life, however, their removal and disposal become both an economic and environmental problem. One possible alternative to low-density polyethylene (LDPE) mulch is provided by certified soil-biodegradable mulch films, such as those produced by Novamont and commercially available under the trade name MaterBi®. MaterBi is a biodegradable thermoplastic material made with starch and a biodegradable copolyester based on proprietary technology. In this study, we compared two biodegradable MaterBi®-based films (commercial and experimental films) with bare soil and a low-density polyethylene to evaluate their effect on yield and on a number of qualitative characteristics (organoleptic and nutraceutical composition) of eggplant fruits (cv Mirabelle F1) grown in two different regions in Southern Italy (Sicily and Campania). In our study, the use of biodegradable MaterBi® films improved not only yield and production parameters, such as the number and average weight of fruits, but also lipophilic and hydrophilic antioxidant activity and phenolic and ascorbic acid content. For many parameters, responses differed according to the cultivation environment and, in particular, the site's pedoclimatic conditions. Our results suggest that biodegradable MaterBi®-based mulching films are a potentially valid alternative to traditional LDPEs, providing the production and quality benefits reported above and promoting environmental sustainability, thanks to their positive biodegradable properties.

Keywords: sustainable agricultural practices; biodegradable mulching; lipophilic antioxidant activity; total phenols; eggplant

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1. Introduction

The eggplant (*Solanum melongena* L.) belongs to the Solanaceae family and it is one of the most widespread horticultural crops worldwide, adapting to environmental conditions in both tropical and subtropical climates [1,2]. In Europe, the main eggplant producers are located in the Mediterranean region: Turkey, Italy, Spain, Greece and France, contributing 20% of total world production. Over 50% of European eggplants are produced in Turkey and Italy alone [3].

The limited availability of cultivable land and huge increases in the world population have led to a growing demand for food. This creates the need for more sustainable crop management techniques with minimal environmental impact [4], including mulching [5].

Mulching is an agricultural practice commonly used since the mid-1950s as it provides a number of benefits, including the conservation of soil moisture, soil temperature regulation, weed control and the protection of crops from pests and various diseases, thereby reducing the need for pesticides and herbicides. Based on their color (black, white, red, green or yellow), they absorb and/or reflect sunlight, affecting the soil temperature in different ways and influencing the growth and productivity of crops [6].

Most films used nowadays are made of petroleum-based plastic materials, amongst which is low-density polyethylene (LDPE), the most-used material thanks to its mechanical and thermo-optical performance, chemical resistance, photo-degradation and microbial degradation resistance, coupled with easy workability and low cost [7]. However, the environmental impacts associated with the use and disposal of low-density polyethylene plastic mulching films are cause for particular concern [8].

Furthermore, polyethylene films (LDPE type), made with non-renewable fossil sources, can only be used for one season and cannot be recycled due to pesticide residues and soil contamination [8,9]. Micro- or nanoparticles generated from non-biodegradable materials can persist in soil and influence microbial activity, soil physical properties and nutrient availability [10]. In addition, the removal and disposal of plastic film residues is highly labor-intensive.

To overcome the problem of substantial quantities of plastic waste, biodegradable and renewable raw materials can be used to produce mulching films. A variety of biodegradable plastic films composed of different polymers and additives are available on the market [11], and yields similar to those obtained with LDPE films have already been reported for many crops [12–19].

Unlike LDPE-based films, biodegradable mulch films can be incorporated directly into the soil or placed in a composting plant. At the end of their life, biodegradable materials decompose in the soil as a result of the microbial community, which mineralizes the material into carbon dioxide, methane, water and biomass, without the production of toxic substances [20,21]. Any biodegradable material is designed to dissolve into the soil in approximately 24 months [22,23]. Furthermore, biodegradable films allow better management of soil temperature, reducing variations in temperature between day and night [24]. Vox et al. [25], in a case where the film remains intact for the entire crop cycle, report a greater capacity of the black MaterBi® film to maintain the heat of the soil and induce earliness compared to the use of LDPE.

Acharya et al. [26] report that biodegradable films increase the humus content of the soil when buried, improve soil structure and promote the free exchange of gases between soil and the atmosphere, thereby determining greater soil porosity, reducing soil compaction and formation of surface crusts, improving soil drainage and reducing wind erosion.

To our knowledge, this study represents one of the few works in which MaterBi® mulching sheets are applied in the cultivation of eggplants in an open field.

The aim of this study was to evaluate the agronomic response of the "Mirabelle F1" eggplant grown in open fields in two different regions in Southern Italy, using two MaterBi® mulching films, with different compositions, one bare soil and one covered with polyethylene film. The findings of this study will elucidate the environment × mulch interaction to select the best combination able to improve the crop performance and nutritional value of this important vegetable. We also believe that these results will be of great interest to horticulturists, extension specialists and scientists.

2. Materials and Methods

2.1. Experimental Sites and Design

This research was carried out during the spring–summer of 2022 in two different regions in Southern Italy. An experimental site was located in Sicily in farm land around Castelvetrano (TP) at the "Campo Carboj" experimental farm belonging to the Region of Sicily's Agricultural Development Agency (Ente di Sviluppo Agricolo, ESA), (37°35′18.0″ N, 12°53′44.0″ E), while the other experimental site was located in Campania at the "Viscusi

Bruno" private farm in Sant'Agata dei Goti (BN) (41°08′05.3″ N, 14°28′57.8″ E). The soils of the two experimental sites had different physiochemical properties, reported in detail in Table 1; soil from the Sicilian site was sandy–clay–loamy, while the Campania soil was clay–sandy with a higher content of P_2O_5 and K_2O.

Table 1. Chemical–physical properties of the experimental site soils.

Parameters	Unit of Measure	Sicily	Campania
Sand	%	64	35
Silt	%	13	25
Clay	%	23	40
N total	g kg^{-1}	1.3	0.9
P_2O_5	mg kg^{-1}	21	69
K_2O	mg kg^{-1}	136	311
Organic matter	%	1.46	1.50
pH		7.0	6.9

The experimental randomized complete block design with three replications was a factorial combination, with the cultivation environment (region) as the first factor and the mulching film as the second factor (mulch). In particular, the mulching treatments were (i) an experimental MaterBi® biodegradable black film, 15 µm in thickness, (Novamont SpA, Novara, Italy), BION1; (ii) a commercial black MaterBi® film, 15 µm in thickness, (Novamont SpA, Novara, Italy), BION4; (iii) black low-density polyethylene film, 50 µm in thickness, LDPE; (iv) bare soil, BS. The width of all films was 1 m. MaterBi® (Novamont S.p.A., Novara, Italy) is reportedly one of the new prospective biodegradable polymers used in agriculture. It is a starch-based material certified as completely biodegradable in soil according to European standard EN 17033. The BION1 film has a higher content of bio-based renewable materials than BION4.

The films were placed manually the day before the transplant, which was carried out in both sites on 10 May 2022, with a distance of 1.70 m between the rows and 0.50 m along the row, thus obtaining a density of approx. 1.2 plants/m^{-2}. The size of each replication plot was 1.70 m × 5.0 m.

2.2. Plant Material and Crop Management

The tested crop was the eggplant cv "Mirabelle" (Bayer Seminis), a hybrid recommended for open field cultivation with long, black, cylindrical fruit, resistant to transport and suitable for both the fresh market and the processing industry [27]. The fertilization plan adopted included the administration of 170 kg ha^{-1} of N in the form of calcium nitrate (15.5%). In both experimental sites, irrigation was managed using a drip system, returning 100% of the evapotranspiration (calculated by the Hargreaves method) [28]. Pest control was performed following integrated control specifications and the use of plant protection products to control mites, leaf miners, Colorado beetles and whiteflies. During the entire cultivation cycle, weed control for the bare soil treatments was performed manually twice. Subsequently, when the plants took on an expanded habitat, rare manual weeding interventions were necessary in conjunction with harvesting.

2.3. Meteorological Data

Precipitation and air temperature data for the Sicilian site were collected at a meteorological station belonging to the Sicilian Agrometeorological Information Service (SIAS) [29]. The station is located approx. 600 m from the experimental field. The station is equipped with a datalogger and various sensors for measuring air temperature (PT100 platinum TAM sensor, thermoresistance with anti-radiant screen) and total rainfall (PPR sensor with tipping bucket pluviometer). Data relating to average daily maximum and minimum temperatures (°C) and total precipitation (mm) were taken into consideration. For the

Campania site, air temperature and rainfall data were collected at the meteorological station of Airola (BN) [30].

2.4. Yield Measurements

At the Sicilian experimental site, there were 7 harvests: the first one on 11 June, the second one after approx. 30 days and successive harvests every 8–10 days, according to climate conditions, until 31 August. In Campania, there were 13 harvests from 21 June to 2 September, approx. every 6 days. Harvesting was performed on a sampling area of approximately 4 m^2, corresponding to 5 plants per replicate. At each harvest, the number and weight of marketable and non-marketable fruits were determined; the non-marketable fruits were those which were deformed, rotting or of a color not typical of the variety. To determine the percentage of fruit dry matter, a representative sample for each treatment and replicate during the second and third harvests was weighed and then dried in an oven at 60 °C until a constant weight was reached.

2.5. Analysis of Fruit Firmness and Colorimetry

During the 3rd harvest, on a sample of ten marketable fruits per treatment and replication, color and firmness parameters were determined. CIElab color parameters (L*: brightness, between 0 (black), no reflection, and 100 (white); a*, chromatic parameter between −60 (green) and +60 (red); b*, chromatic parameter between −60 (blue) and +60 (yellow) were determined using a Chromameter CR-400 (Minolta Corporation, Ltd., Osaka, Japan). Coloration (C*) and hue angle (H°) were also calculated as follows: C* = (a*2 + b*2)1/2; HUE = (arctan (b*/a*)). Fruit firmness was determined using a digital penetrometer with an 8 mm tip (Turoni srl, Italy). Values were expressed in Newton (N).

2.6. Qualitative Analysis

For each treatment and replicate, a sample of 10 eggplant fruits was collected, frozen at −80 °C and successively lyophilized with a lyophilizer Crist, Alpha 1–4 (Osterode, Germany), to determine hydrophilic and lipophilic antioxidant activity and total phenolic content. Chlorophyll, carotenoid and ascorbic acid contents were measured in fresh samples. Chlorophyll pigments and carotenoids were measured in 1 g of fresh sample according to the Lichtenhaler and Wellburn method [31]. The samples were extracted with ammoniacal acetone; absorbance of the solution of chlorophyll a, chlorophyll b and carotenoids was then measured at 662, 647 and 470 nm, respectively, with a spectrophotometer (Hach DR 2000, Hach Co., Loveland, CO, USA); total chlorophyll is the sum of chlorophylls a and b. Values were expressed as mg g^{-1} fresh weight (fw). The Kampfenkel et al. [32] method was used to measure total ascorbic acid content, which was expressed as mg of ascorbic acid per 100 g^{-1} fw. Meanwhile, total phenolic content was determined according to the procedure described by Singleton et al. [33] and expressed in mg of gallic acid per 100 g^{-1} of dry weight (dw). Antioxidant capacity analysis was carried out on 200 mg of freeze-dried eggplant fruit extract prepared using a freeze-dryer (Christ, Alpha 1–4, Osterode, Germany); hydrophilic (HAA) and lipophilic (LAA) antioxidant activity was evaluated by the N, N-dimethyl-p-phenylenediamine (DMPD) [34] and ABTS (2,20-azinobis 3-ethylbenzothiazoline-6-sulfonic acid) [35] methods. Values were expressed as mmol of ascorbic acid 100 g^{-1} dw for HAA and mmol of Trolox 100 g^{-1} dw for LAA. One dried sample of eggplant fruit per replicate was used to measure the nitrate content, using a Foss FIAstar 5000 continuous-flow analyzer. The method is based on the reduction of nitrate to nitrite on a cadmium reducer [36]. The value was expressed as a percentage of nitrogen in nitrate form ($N\text{-}NO_3$) on dry weight.

The Kjeldahl method was used to measure the nitrogen concentration in fruits; the value was then transformed into protein content (N content × 6.25). Values were reported in percentages (%) [37].

2.7. Statistical Analysis

All data were subjected to 2-way analysis of variance (ANOVA) using the MINITAB 19.1.1.0 (State College, PA, USA) software package for Windows. To ensure compliance with ANOVA assumptions, all data were tested for normality and variance homogeneity through the Ryan–Joiner test (α = 0.05) and Levene's test (α = 0.05). Experimental factors were region (R) and mulch (M) (MaterBi and PE). The means were separated using Tukey's test at $p \leq 0.05$.

3. Results

3.1. Rainfall and Air Temperature Trends at the Two Experimental Sites

During the cultivation cycle, similar rainfall levels were found, 84 mm in Campania and 75 mm in Sicily, with considerable differences in the distribution (Figure 1). In Sicily, 74% of rain was concentrated in May and, in particular, in the first 10-day period (47 mm), there was no rain in Sicily in June and July (Figure 1A). In Campania, rain distribution was more uniform, with no excessively prolonged drought periods; however, 58% of rain was concentrated in the last month of the cycle (Figure 1B).

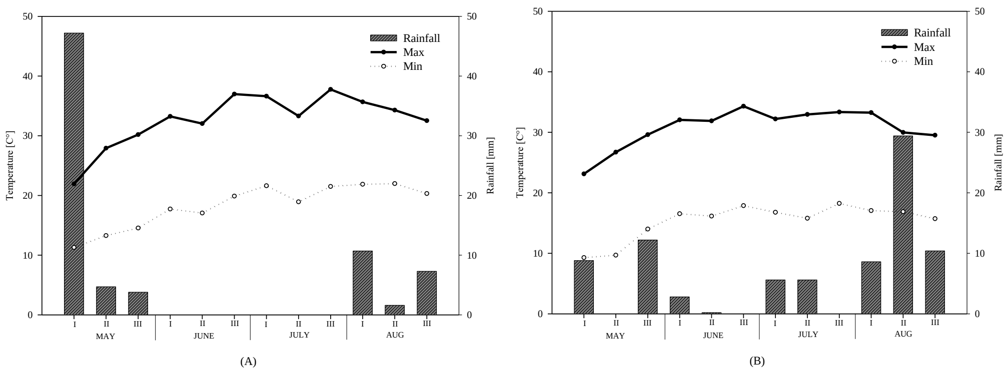

Figure 1. Temperature and rainfall trends at the experimental sites in Sicily (**A**) and in Campania (**B**).

Regarding temperatures, both environments reported increases until the end of July; in Campania, average temperatures were always lower than in Sicily (23.0 °C vs. 25.5 °C), and the difference between maximum and minimum temperatures was greater (15.4 °C vs. 14.4 °C) (Figure 1).

3.2. Yield Parameters

Analysis of variance showed that all parameters of production (with the exception of average marketable fruit weight) were affected by the R $\times$ M interaction; in addition, they were also significantly influenced by the environment (region) and mulching, except marketable yield and average non-marketable fruit weight, respectively (Table 2). As shown in Figure 2, the highest marketable yield was observed in Sicily with biodegradable film BION4, which did not differ from BION1. In turn, BION1 did not differ from the corresponding treatment in Campania. In contrast, BION4 in Campania showed lower values and did not differ from LDPE. Finally, the lowest marketable yield was observed in Sicily for bare soil plants (Figure 2). As regards the non-marketable yield, the highest values were recorded in Sicily (Table 2) for all three mulching films with no differences between them; no differences were recorded between all the other treatments (Figure 2).

In addition, the number of both marketable and non-marketable fruits was higher in Sicily: +40.9% and + 25.3%, respectively (Table 2; Figure 3). In particular, regarding both the marketable yield and the number of marketable fruits, the highest values were recorded for the commercial Materbi® (BION4), followed by BION1 and LDPE; in Campania, however, differences between treatments were less evident; in fact, only BION1 was different from bare soil (Figure 3). In both regions, bare soil showed the lowest and non-significant differences (Table 2; Figure 3). As regards the number of non-marketable fruits, the highest values were obtained from plants grown in Sicily on mulching films, irrespective of typology; it is interesting to note that, in Campania, bare soil showed non-different values from the other treatments (Figure 3).

Table 2. Effect of type of mulching (M) and region (R) on eggplant yield parameters.

Treatments	MY [kg m^{-2}]	NMY [kg m^{-2}]	MF [n. m^{-2}]	NMF [n. m^{-2}]	AMFW [g]	ANMFW [g]
Region (R)						
Sicily	7.6 ± 0.6	1.5 ± 0.2 a	57.9 ± 4.1 a	11.4 ± 1.1 a	130.0 ± 2.9 b	134.3 ± 6.9 a
Campania	7.4 ± 0.2	0.9 ± 0.1 b	41.1 ± 0.9 b	9.1 ± 0.3 b	180.9 ± 1.4 a	104.2 ± 1.6 b
Mulching (M)						
BS	5.4 ± 0.5 c	0.9 ± 0.1 b	36.5 ± 0.6 c	7.6 ± 1.0 b	156.5 ± 12.1 a	116.4 ± 7.9
LDPE	7.8 ± 0.1 b	1.4 ± 0.2 a	51.1 ± 4.6 b	12.1 ± 1.3 a	157.9 ± 12.6 a	115.2 ± 3.1
BION1	8.5 ± 0.2 a	1.3 ± 0.2 a	54.3 ± 4.2 a	10.6 ± 1.1 a	161.2 ± 10.2 a	123.0 ± 12.4
BION4	8.4 ± 0.4 a	1.4 ± 0.2 a	56.1 ± 6.8 a	10.7 ± 0.9 a	146.4 ± 11.4 b	122.4 ± 9.3
Significance	***p*-value**					
R	0.173	0.000	0.000	0.000	0.000	0.000
M	0.000	0.000	0.000	0.000	0.003	0.059
R × M	0.000	0.000	0.000	0.000	0.589	0.004

MY: marketable yield; NMY: non-marketable yield; MF: marketable fruits; NMF: non-marketable fruits; AMFW: average marketable fruit weight; ANMFW: average non-marketable fruit weight. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®. Within each column, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

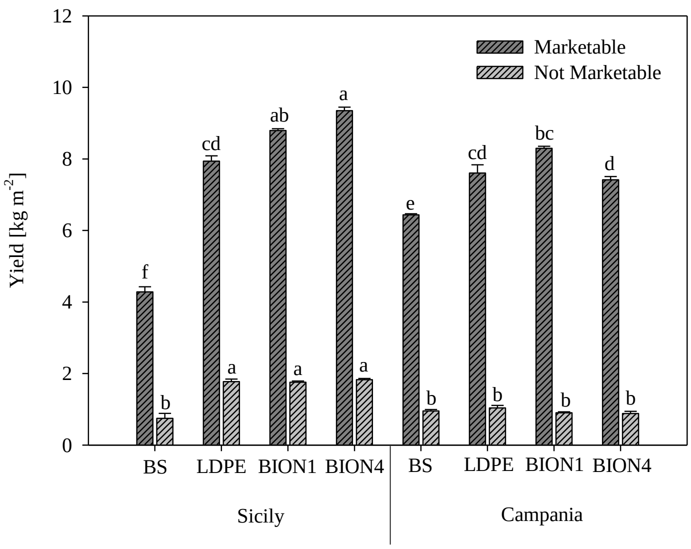

Figure 2. Influence of the Region × Mulching interaction on marketable and non-marketable yield. For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

Finally, the average weight of marketable fruits was significantly higher in Campania, while, as regards the effect of mulching, Campania showed the lowest value in BION4 (Table 2). In contrast, the average weight of non-marketable fruits was higher in Sicily (Table 2), with no significant differences between the two biodegradable mulching films and bare soil; the lowest values were recorded in Campania with no differences between all treatments (Figure 4).

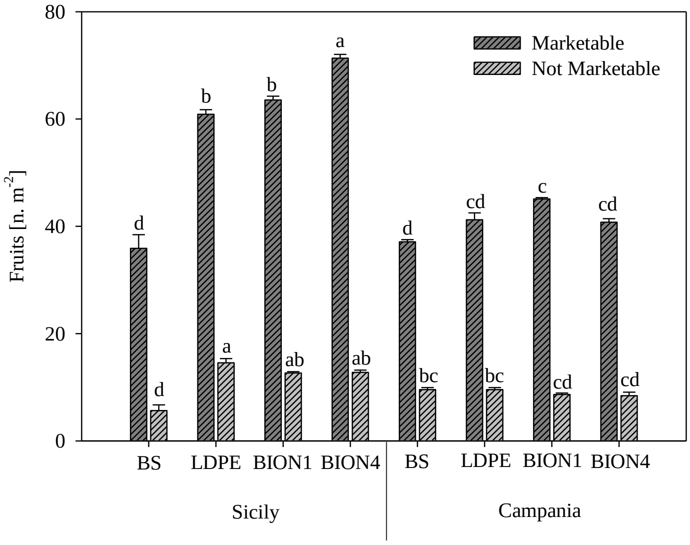

Figure 3. Influence of the Region × Mulching interaction on the number of marketable and non-marketable fruits. For each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

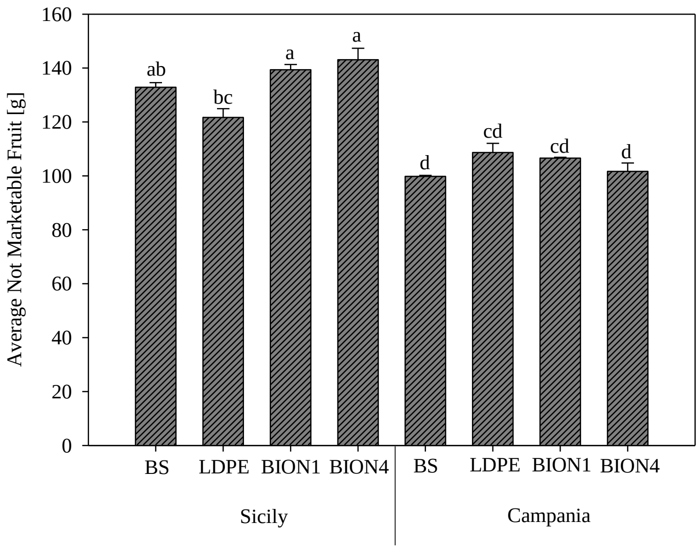

Figure 4. Influence of the Region × Mulching interaction on average non-marketable fruit weight. Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

3.3. Qualitative Parameters

Analysis of variance showed that firmness and dry matter percentage of eggplant fruits were significantly affected by the region; in addition, firmness was also influenced by mulching and the Region × Mulching interaction (Table 3). In particular, higher firmness values were recorded in Sicily than in Campania, with a 56.2% average increase (Table 3; Figure 5). The greatest firmness was obtained in plants cultivated on traditional plastic mulching in Sicily, and it was significantly different from all other treatments (Figure 5). Notably, in Campania, no differences were recorded between mulching treatments (Figure 5). The dry matter percentage of fruits reached its highest value in Campania (Table 3).

Table 3. Effect of region (R) and mulching (M) on firmness and dry matter of eggplant fruits.

Treatments	Firmness [N]	Dry Matter [%]
Region (R)		
Sicily	25.3 ± 0.7 a	6.8 ± 0.1 b
Campania	16.2 ± 0.2 b	8.5 ± 0.1 a
Mulching (M)		
BS	21.0 ± 1.9 ab	7.8 ± 0.5
LDPE	22.0 ± 3.0 a	7.4 ± 0.3
BION1	20.0 ± 1.8 b	7.4 ± 0.4
BION4	20.0 ± 1.6 b	7.8 ± 0.4
Significance	***p*-value**	
R	0.000	0.000
M	0.014	0.100
R × M	0.000	0.177

BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®. Within each column, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

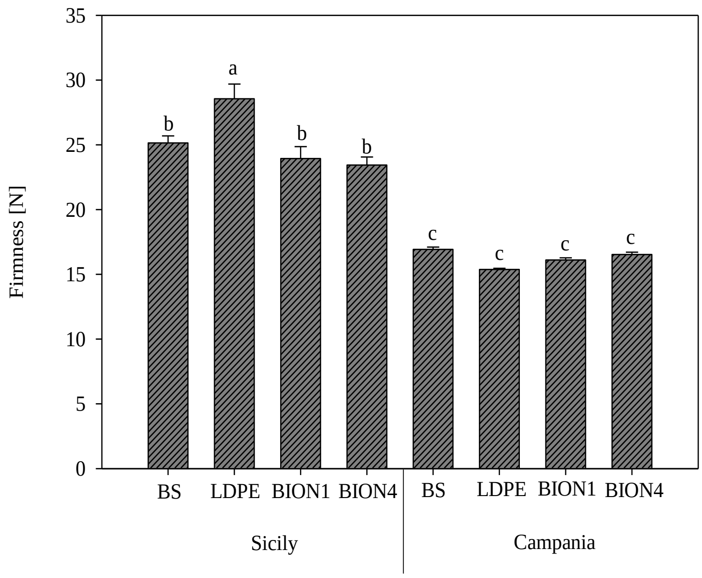

Figure 5. Influence of the type of mulching on eggplant firmness. Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

3.4. Antioxidant Activity and Bioactive Compounds

The statistical analysis highlighted a significant effect of the R × M interaction only for hydrophilic and lipophilic antioxidant activity (HAA; LAA); HAA and ascorbic acid were affected by region, while mulching influenced LAA, total phenols and ascorbic acid; no significant effects were recorded for carotenoid content (Table 4). In particular, the highest total phenolic content was obtained with the two biodegradable films, which were not different, however, from the LDPE film, while the lowest content was recorded for bare soil (Table 4). The highest ascorbic acid content was obtained in Campania (+75.5%) compared to the Sicily value (Table 4); moreover, mulching elicited a higher value of ascorbic acid, irrespective of type (+49.0% compared to bare soil) (Table 4).

Higher values were obtained for HAA in Sicily (+35.1% compared to Campania) (Table 4) and, in particular, using BION1 (6.8 mM ascorbic acid equivalent 100 g^{-1} dw), which was not different from both bare soil in Sicily and LDPE in Campania (Figure 6). In contrast, in Campania, the two biodegradable films and bare soil showed lower values, with no difference between them or LDPE and BION4 in Sicily (Figure 6).

Table 4. Effect of type of mulching (M) and region (R) on eggplants' hydrophilic antioxidant activity (HAA), lipophilic antioxidant activity (LAA), total phenols, vitamin C and carotenoids.

	HAA [mM AA eq. 100 g^{-1} dw]	**LAA [mM Trolox eq. 100 g^{-1} dw]**	**Total Phenols [mg GA g^{-1} dw]**	**Ascorbic Acid [mg 100 g^{-1} fw]**
Region (R)				
Sicily	5.0 ± 0.4 a	21.4 ± 1.3	2.9 ± 0.3	39.6 ± 3.2 b
Campania	3.7 ± 0.3 b	20.1 ± 2.0	2.5 ± 0.1	69.5 ± 3.5 a
Mulching (M)				
BS	4.3 ± 0.5	17.4 ± 0.8 bc	2.1 ± 0.1 b	39.9 ± 5.5 b
LDPE	4.7 ± 0.4	16.2 ± 2.5 c	2.5 ± 0.3 ab	64.4 ± 6.1 a
BION1	5.0 ± 0.9	25.5 ± 1.1 a	3.0 ± 0.4 a	55.4 ± 9.3 a
BION4	3.5 ± 0.4	24.0 ± 1.7 ab	3.1 ± 0.2 a	58.5 ± 7.6 a
Significance	***p*-value**			
R	0.013	0.453	0.141	0.000
M	0.215	0.002	0.048	0.000
R × M	0.000	0.000	0.170	0.113

BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®. Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

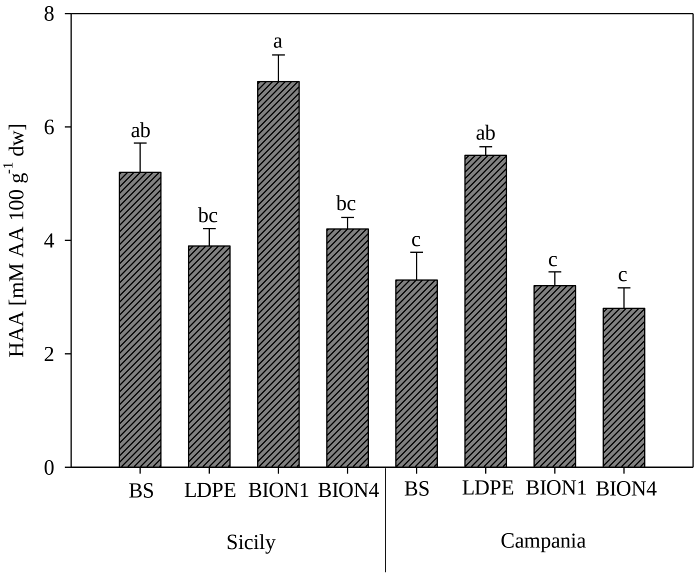

Figure 6. Influence of the Region × Mulching interaction on the hydrophilic antioxidant fraction (HAA). Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

As regards the lipophilic antioxidant activity (LAA), the highest value (27.82 mM Trolox 100 g^{-1} dw) was observed with the combination Campania × BION4; however, it was not different from BION1 both in Sicily and in Campania (Figure 7). The treatment Campania × LDPE showed the lowest LAA (10.8 mM Trolox 100 g^{-1} dw) (Figure 7).

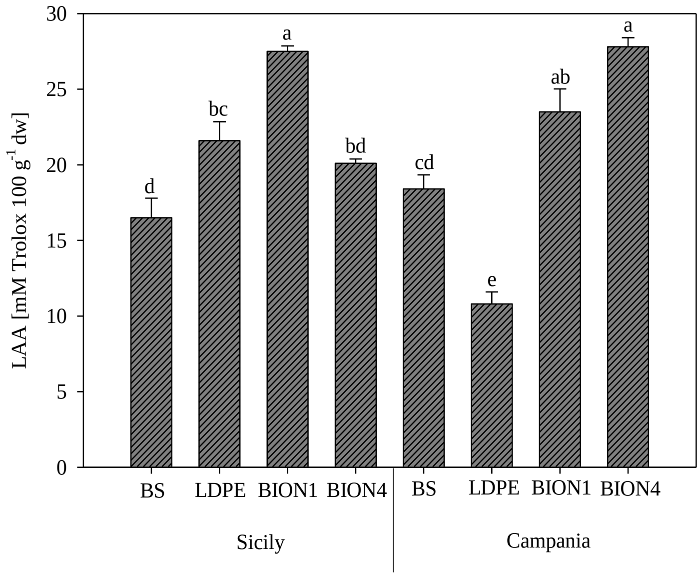

Figure 7. Influence of the interaction Region × Mulching on lipophilic antioxidant activity (LAA). Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard deviation. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

3.5. Chlorophyll, Nitrate and Protein Content

Analysis of variance showed a significant effect of the R × M interaction only for N-NO_3 (Table 5). The main effect of mulching was not significant; instead, all parameters were affected by region, with the highest values observed persistently in the Campania Region (Table 5).

Table 5. Effect of type of mulching (M) and region (R) on chlorophyll, nitrate and protein content of eggplants.

	Chlorophyll a [mg g^{-1} fw]	Chlorophyll b [mg g^{-1} fw]	Tot. Chlorophyll [mg g^{-1} fw]	N-NO_3 [% dw]	Proteins [%]
Region (R)					
Sicily	0.020 ± 0.004 b	0.016 ± 0.003 b	0.036 ± 0.006 b	0.027 ± 0.005 b	11.5 ± 0.2 b
Campania	0.050 ± 0.007 a	0.027 ± 0.003 a	0.077 ± 0.009 a	0.071 ± 0.006 a	14.6 ± 0.3 a
Mulching (M)					
BS	0.040 ± 0.012	0.023 ± 0.005	0.063 ± 0.016	0.057 ± 0.017	13.1 ± 1.0
LDPE	0.031 ± 0.006	0.019 ± 0.003	0.050 ± 0.009	0.059 ± 0.012	13.2 ± 0.7
BION1	0.032 ± 0.013	0.018 ± 0.007	0.050 ± 0.019	0.046 ± 0.012	13.0 ± 0.6
BION4	0.036 ± 0.008	0.025 ± 0.004	0.061 ± 0.011	0.034 ± 0.003	12.9 ± 0.6
Significance	***p*-value**				
R	0.001	0.011	0.002	0.000	0.000
M	0.856	0.482	0.766	0.118	0.912
R × M	0.383	0.094	0.251	0.000	0.529

Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

As shown in Figure 8, the highest N-NO_3 content (0.093%) was recorded in Campania without mulching, and it was not different from LDPE and BION1–Campania (Figure 8). The lowest values were observed in Sicily (Figure 8).

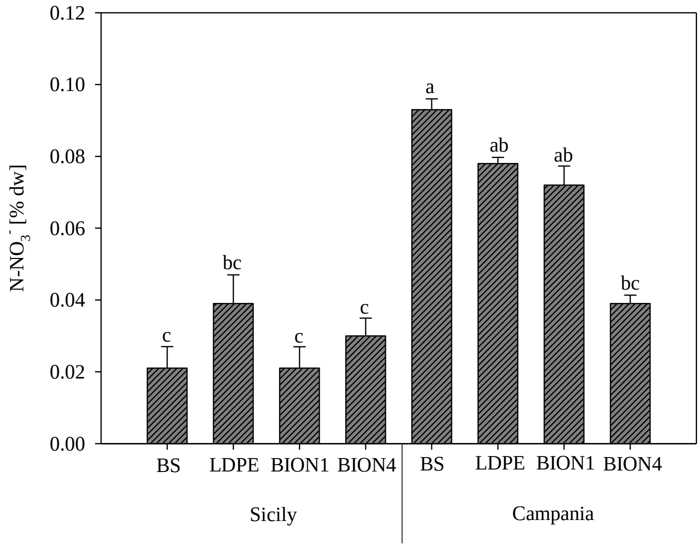

Figure 8. Influence of the Region × Mulching interaction on nitrates (N-NO_3^-). Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

3.6. Color Parameters

As regards the color parameters, ANOVA highlighted a significant effect of the interaction R × M only for brightness (L*); the main effect of the region was significant for all three parameters, while mulching significantly affected only L* (Table 6). The highest brightness values (L*) were observed with the four mulching treatments in Sicily; however, they did not differ statistically from those obtained in Campania with the two biodegradable films. The latter films, in turn, were not different from all other treatments (Figure 9; Table 6).

Table 6. Effect of the type of mulching on color parameters L* (brightness), C (chroma), and H (hue angle) of eggplant fruits.

	L*	C	H
Region (R)			
Sicily	25.5 ± 0.2 a	5.5 ± 0.4 b	0.13 ± 0.02 a
Campania	23.0 ± 0.4 b	6.8 ± 0.3 a	0.02 ± 0.01 b
Mulching (M)			
BS	24.0 ± 0.9 ab	5.6 ± 0.3	0.04 ± 0.03
LDPE	23.5 ± 0.8 b	5.9 ± 0.6	0.07 ± 0.02
BION1	24.7 ± 0.4 ab	6.6 ± 0.7	0.11 ± 0.05
BION4	25.0 ± 0.5 a	6.3 ± 0.4	0.07 ± 0.02
Significance	***p*-value**		
R	0.000	0.015	0.000
M	0.028	0.433	0.078

Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

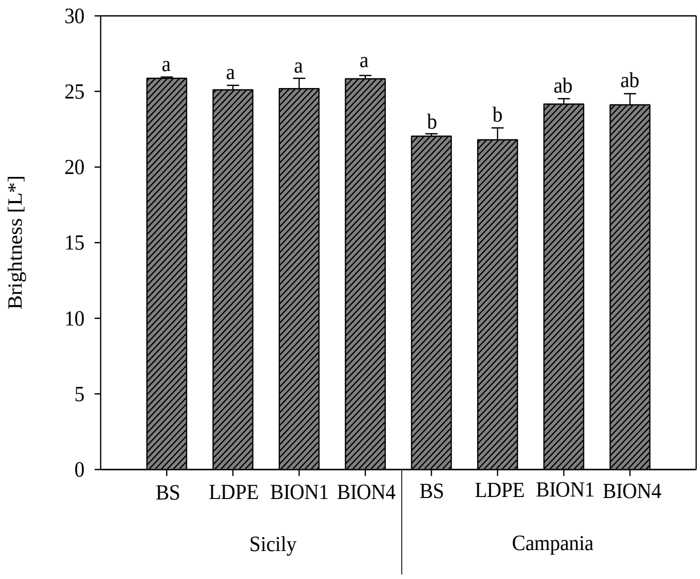

Figure 9. Influence of the Region × Mulching interaction on brightness (L*). Values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Error bars represent standard error. BS: bare soil; LDPE: low-density polyethylene; BION1: experimental MaterBi®; BION4: commercial MaterBi®.

4. Discussion

Reducing the environmental impact of agronomic practices is one of the hardest challenges to beset modern agriculture. Amongst the possible sustainable approaches, the use of biodegradable plastic films for soil mulching undoubtedly deserves our attention. The use of biodegradable films has become a consolidated practice in recent years [13], not only due to environmental benefits but also as a result of increases in yield and improvements in quality, as reported in many crops [13,18,19,38–40]. However, to date, there are few studies available in the literature with agronomic data on the use of biodegradable films for mulching in eggplants cultivated in open fields. Therefore, this research aimed to evaluate the effects of two biodegradable films (a commercial and an experimental film) on yield and on a number of qualitative characteristics in eggplants grown in two different regions in Southern Italy, compared to a traditional polyethylene film and bare soil.

In general, mulching persistently elicited an increase in yield compared to the non-mulched soil, and it was mainly due to a greater number of fruits. In particular, the biodegradable mulching performed better than LDPE; however, behavior differed between the two environments. In Sicily, both films obtained a yield that was significantly higher than traditional LDPE, while in Campania, only the experimental MaterBi® film (BION1) showed similar productive performance (without differing from LDPE). Previous studies reported similar findings for biodegradable mulching. Di Mola et al. [17], in an open-field trial on processing tomatoes with two different biodegradable mulches (including MaterBi®), obtained higher marketable yields compared to the non-mulched soil. Cozzolino et al. [19] also obtained higher yields and number of fruits when melons were cultivated on MaterBi® films compared to cultivation on LDPE. These authors observed that, under the MaterBi® film, maximum soil temperatures were lower than those under LDPE, and daily temperature variations were less marked. They suggested that the increase in melon yield was due to an improved soil micro-climate [19]. We speculate that this may also have occurred in our test. The different productive behavior of plants in the two experimental sites was probably due to different air temperature trends. In Sicily, temperatures were already higher than in Campania in the first growth period; indeed, the first harvest was carried out 10 days earlier than in Campania. However, in Campania, successive harvests were carried out regularly, approx. every 5–7 days, whilst in Sicily, the second harvest was carried out after 32 days (13 July). In fact, from the middle of June, maximum temperatures began to increase, exceeding 35 °C in the last 10-day period in June and the first 10-day period in July; this may have created problems for the plants. Indeed, Alam and Salimullah [41] report that the optimal temperature for the growth and development of eggplants ranges from 22 °C to 30 °C; supra-optimal temperatures limit plant growth, increase flower drop, reduce fruit settings and productivity, and damage quality. Mohideen et al. [42] report that high temperatures (30–35 °C) impair flowering in varying ways depending on the cultivar. Therefore, we hypothesize that the block of eggplant production observed in Sicily can be attributed to excessively high temperatures. In addition, higher temperatures in Sicily also accelerated seed production in eggplant fruits, which is a negative quality trait. It is extremely important to harvest and consume eggplant fruits when they are immature, before the development of seeds [43], as ripe fruits, in addition to the large quantity of ripe seeds, are far less attractive due to the unpleasant color, poor firmness, and pronounced and bitter taste [41]. In Sicily, in order to avoid seeds, fruits are harvested when smaller. It is also possible that the greater number of non-marketable fruits in Sicily may be due to excessively high air temperatures. On the other hand, in a tomato test reported by Dalbianco et al. [44], regarding plants grown on mulching (higher soil temperatures), a greater number of non-marketable fruits was recorded compared to those cultivated on non-mulched soils.

The quality of vegetables is defined both by external attributes, such as color, shape, size and freshness, as well as internal characteristics such as firmness, flavor, mineral content, health-promoting compounds and sensory parameters. In particular, the evaluation of fruit firmness is important both for the organoleptic characteristics and shelf life of eggplant fruits [45], and it can be influenced by several factors, including soil nitrogen availability. Radicetti et al. [46] noted that, when eggplant cultivation is preceded by a legume crop, fruit firmness is greater compared to firmness levels recorded when preceded by grasses and brassicas. In effect, in our research, we found that firmness was higher in Sicily where soil nitrogen content was higher than that measured in Campania. Firmness is also linked to the intrinsic characteristics of the fruit, such as size, stage of ripeness, thickness of the cuticle and natural waxes on the surface of the fruit [47]. Furthermore, it is possible that the greater firmness of eggplant berries in the Sicilian site was also due to smaller and slightly less mature fruits. In addition, the effect of mulching on fruit firmness was different in the two sites: in Campania, mulching did not affect firmness, similar to results obtained by Cozzolino et al. [19] in melons and Cowan et al. [48] in tomatoes; in Sicily, only LDPE elicited the highest value of firmness. This result is partially in line with the findings of Moreno et al. [49], who recorded a slightly higher value of firmness in tomato fruits grown on PE, although not significantly different from biodegradable films (4.37 vs. 4.15 kg cm^{-2}, mean value of an oxo-biodegradable and two biodegradable films).

The percentage of dry matter was influenced only by the cultivation environment, with the highest levels in Campania. This difference could be due to the different textures of the two experimental soils: in Campania, the soil had a higher clay content than in Sicily (40% vs. 23%) and, thus, a probable greater availability of some nutrients [50,51]. On the other hand, our finding is also in line with the results of Cozzolino et al. [19] on melons.

Antioxidant activity can be divided into hydrophilic and lipophilic activity, depending on the nature of the examined antioxidant compounds. In eggplant fruits, it mainly depends on the content of anthocyanins and phenolic acids [52,53]. In our research, both antioxidant activities were affected by the combined effect of the environment and mulching film. In particular, we highlighted a contrasting response of HAA to biodegradable mulching, contrary to previous studies on tomatoes [17,54] and strawberries [6], which report a positive influence of biodegradable films on hydrophilic antioxidant activity. In fact, only in Sicily, the experimental Materbi® obtained a high level of HAA, while the other biodegradable film in Sicily and both films in Campania showed lower values. On the contrary, it is interesting to note that plants mulched with both MaterBi® films produced the highest LAA content in Campania, in addition to those grown on BION1 in Sicily.

Although these results have never been reported in the literature regarding eggplants, they have been confirmed for other species [6,19,55].

Eggplants are classified as one of the top ten vegetables in terms of their ability to remove free radicals [56]. This activity has been correlated to the content of phenolic compounds [57], which are associated with numerous health benefits, including the ability to protect against cancer, reduce inflammation, support heart health by lowering total cholesterol, LDL cholesterol and triglycerides, and reduce the risk of atherosclerosis, thanks to their antioxidant function [58–62]. In general, the phenolic content of eggplant fruits mainly depends on the cultivar and pre-harvest factors, such as environment and agricultural practices [57]. In our study, the highest total phenolic content was obtained in fruits of plants grown on mulching, with the highest values in both MaterBi® films, in agreement with other studies [19,63]. However, it seems that quality improvement could be due to species-specific responses to mulching film type and to growing conditions and/or other agricultural practices [12,64,65].

Ascorbic acid content is a very important parameter for eggplant fruits as it prevents browning of the fruit after cutting. In this study, both the test environment and mulching significantly influenced ascorbic acid content. The highest content was obtained in the Campania site, leading to the assumption that, as was the case of other variables considered in this study, differing pedoclimatic conditions led to decreases in ascorbic acid content, possibly due, in particular, to higher temperatures found in the Sicilian site. In fact, several authors [66,67] report that ascorbic acid content in eggplant fruits depends not only on the genotype but also on the environment and the developmental stage. The synthesis of sugars, ascorbic acid and polyphenols is conditioned by development and reaches maximum values approximately 6 weeks after the eggplant has set. Therefore, it is important to consider this when seeking the optimal harvesting time, that is, when eggplant fruits have a higher nutritional value [68]. In agreement with Ayyar et al. [69], Morra et al. [54] and Di Mola et al. [17], plants grown on mulched soil accumulate a greater quantity of ascorbic acid compared to bare soil; therefore, it can be assumed that lower temperature changes and greater water availability due to mulching films are able to guarantee a greater accumulation of ascorbic acid [70–72].

Nitrogen is one of the main factors which influences the formation of chlorophyll [73]. Differences in the chlorophyll content of eggplant fruits in the two experimental sites could be attributed to both differing soil textures and temperature conditions, which make nitrogen more or less available for plants [46]. In general, in our research, the nitrate and protein contents were higher in the Campania Region; in particular, the nitrate content was affected by the combined effect of environment and mulching. In Sicily, no differences were found between bare soil and all three mulching treatments regarding nitrate content, while in Campania, the highest value was recorded in the fruits of plants grown on bare soil; however, it differed only from BION4.

Finally, as regards the qualitative traits of the eggplant fruit, peel color is of primary importance as the pigments which provide the color are associated not only with visual preferences but also with nutritional, health and taste values [74]. The dark purple color of the epicarp and the shine of the peel progressively increase before the ripening phase [75]. In our research, we found that brightness and hue angle were higher in Sicily, in contrast to chroma; mulching, however, affected only brightness. In fact, the highest value was recorded in BION1, differing only from LDPE.

5. Conclusions

Our findings indicate that the use of biodegradable mulching films can represent a valid and sustainable alternative to traditional low-density polyethylene. Indeed, as reported for other species, biodegradable mulching in eggplant cultivation produced improvements in yield and some fruit quality traits, such as lipophilic antioxidant activity and phenolic and ascorbic acid content. However, the influence of the environment, alone or combined with mulching, on many quantitative–qualitative parameters was highly evident and attributable to the different pedoclimatic conditions. Therefore, though further research is certainly desirable to verify the environment–mulch–species interaction, these preliminary results would seem to suggest that greater diffusion of biodegradable films is desirable. In addition, the use of biodegradable mulching films makes cultivation systems more sustainable both from an environmental point of view (reduction in soil pollution due to plastics) and from an economic point of view (reduction in cost of removal and disposal).

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