Italian Journal of Agronomy 19 (2024) 100025

Contents lists available at ScienceDirect

Italian Journal of Agronomy

journal homepage: www.sciencedirect.com/journal/italian-journal-of-agronomy

Full Length Article

Biodegradable mulching films affect soil temperature and agronomic performance of open field eggplant in hot-arid environments

Nicolò Iacuzzi[a], Noemi Tortorici[a], Di Mola Ida[b,*], Federica Alaimo[a], Eugenio Cozzolino[c], Mauro Sarno[a], Mauro Mori[b], Teresa Tuttolomondo[a]

[a] *Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, 13, Building 4, Palermo 90128, Italy*
[b] *Department of Agricultural Sciences, University of Naples Federico II, Piazza Carlo di Borbone 1, Portici 80055, Italy*
[c] *Research Center for Cereal and Industrial Crops—Council for Agricultural Research and Economics (CREA), Caserta 81100, Italy*

ARTICLE INFO

Keywords:
Solanum melongena L
Mulch
Sustainable agriculture
Yield
Lipophilic antioxidant activity
Total soluble solids

ABSTRACT

Mulching is a common practice used to increase yields, control weeds and achieve off-season production. When performed with plastic films (such as low-density polyethylene -LDPE), it can lead to a range of environmental and economic issues primarily related to management and disposal at the end of the crop cycle. To address this problem, soil-biodegradable mulching films made from organic materials are becoming increasingly used. Considering that the agronomic responses and plant quality of crops mulched with biodegradable films can vary depending on cultivar, type of biodegradable film, and cultivation conditions, this study aimed to evaluate, over two years of experimental trials (2022–2023) in a hot-arid environment, the effect of two different biodegradable mulching films made from MaterBi® (BION1-experimental; BION4-commercial) on the morphological, physiological, yield, and quality parameters of “Mirabelle F1” eggplant fruits. Additionally, the agronomic response of plants mulched with biodegradable films was compared to that those of plants mulched with LDPE and bare soil (BS). Regarding soil thermal conditions, mulching increased soil temperature by approximately 2 °C compared to BS, while the MaterBi® films reduced daily thermal fluctuations compared to LDPE and BS. Both MaterBi® films improved plant growth, leaf chlorophyll content, and increased yield, primarily due to the greater weight of the fruits compared to LDPE and BS. The BION1 film was associated with improvements in total soluble solids content, chlorophyll, and lipophilic antioxidant activity of the eggplant fruits. For most of the analyzed parameters, responses varied depending on temperature trends during the two years of study, leading us to suggest that MaterBi® films could be a valid alternative to non-biodegradable plastic mulching, particularly in hot-arid environments.

1. Introduction

Since Harold Warp developed the first glass substitute for agricultural use in 1924, a true revolution began, allowing for the modification of the microclimate of crops and enabling cultivation even when temperatures were not ideal (Kasirajan and Ngouajio, 2012). The first technique employed to modify the microclimate was mulching using organic and inorganic materials (Jaworski et al., 1974), but a significant breakthrough occurred in the mid-20th century with the introduction of polyethylene, polyvinyl chloride, and ethylene-vinyl acetate, which gave rise to "plasticulture" (Jensen, 2004). Since then, the consumption of plastic materials in agriculture has quadrupled, reaching 4 % of 400.3 million tons produced in 2022 (Statista, 2023), transforming agriculture from a traditionally low-waste sector into one with significant waste-related issues. Low Density Polyethylene (LDPE), produced from non-renewable fossil sources, can only be used for one season and cannot be recycled due to pesticide residues and soil contamination. Micro- or nanoparticles generated from non-biodegradable materials can persist in the soil and impact microbial activity, physical soil properties, and nutrient availability. Furthermore, the removal and disposal of plastic film residues require substantial labour (Lakhiar et al., 2024).

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* Corresponding author.

E-mail addresses: nicolo.iacuzzi@unipa.it (N. Iacuzzi), noemi.tortorici@unipa.it (N. Tortorici), ida.dimola@unina.it, ida.dimola@unina.it (D.M. Ida), federica.alaimo02@unipa.it (F. Alaimo), eugenio.cozzolino@crea.gov.it (E. Cozzolino), mauro.sarno@unipa.it (M. Sarno), mori@unina.it (M. Mori), teresa.tuttolomondo@unipa.it (T. Tuttolomondo).

https://doi.org/10.1016/j.ijagro.2024.100025
Received 31 October 2024; Received in revised form 18 December 2024; Accepted 19 December 2024

To address this issue, various governments, non-governmental organizations, and companies are making significant efforts to discover solutions and strategies to combat plastic pollution in agriculture. Among the strategies of the R model (Refuse, Reduce, Redesign, Reuse, Recycle, and Recover) (Blanke, 2023), there is the substitution of conventional plastics with natural or biodegradable alternatives, as reported also by Francioni et al. (2022) and Sander (2019). According to Steven and Octiano, 2020, and Vox et al. (2013), bio-based and biodegradable plastics are currently considered the best solutions to achieve sustainability in the sector and provide a vital substitute for petrochemical or conventional plastics in the near future. Indeed, compared to synthetic plastics, biodegradable plastics aim to create a more sustainable and environmentally friendly world with a lower environmental impact. Today, the market offers many types of biodegradable mulching films (Menossi et al., 2021) capable of improving the yield of various crops, often performing comparably (Di Mola et al., 2023, 2022, 2019; Briassoulis and Giannoulis, 2018; Martin-Closas et al., 2017) and in some cases better (Samphire et al., 2023; Kasirajan and Ngouajio, 2012) than LDPE mulching films.

Eggplant (*Solanum melongena* L.) is one of the most widely cultivated crops in the world, with notable differences between countries, primarily due to farmers' ability to overcome the biotic and abiotic stresses faced by the crop (Alam and Salimullah, 2021). Overcoming biotic stress is mainly related to the use of pest and disease control strategies, while overcoming abiotic stress (particularly temperature and drought), especially in open-field cultivation, is challenging. Several authors have reported the effects of biodegradable mulching in mitigating abiotic stresses. Jia et al. (2020) reported a 3 % increase in soil moisture retention with biodegradable films compared to plastic mulching in industrial tomatoes. Chen et al. (2019) observed improved soil water content and water use efficiency in plants mulched with biodegradable films compared to those mulched with plastic films and non-mulched plants. Additionally, some studies have demonstrated that for crops with short life cycles, biodegradable mulching films increase soil temperature and retain moisture better than traditional plastic mulching films (Wang et al., 2020; Song et al., 2024). Finally, as reported by Shi et al. (2024), biodegradable mulching films, due to their organic composition and reduced thickness, are likely able to stabilize daily thermal fluctuations in soil, particularly in environments characterized by high temperatures. Therefore, the present research hypothesizes that the effect of two different biodegradable mulch films (one experimental and one commercial, both MaterBi® based), compared with traditional plastic mulch films, would improve morphological and physiological traits, as well as yield and fruit quality of crops. This study used the eggplant cultivar "Mirabelle F1" as a test crop, also aiming to verify whether the feasibility of substituting of traditional plastic mulching with a biodegradable alternative may limit plastic pollution.

To our knowledge, this study represents one of the few studies where MaterBi® mulching films have been applied in the cultivation of eggplants in open fields, and the only study where not only yield and quality parameters are evaluated but also soil temperatures and the morphological and physiological parameters of the crop.

2. Materials and methods

2.1. Experimental sites and design

The experiment was carried out in Sicily, Castelvetrano (TP), at the experimental farm "Campo Carboj", owned by the Agricultural Development Authority of the Sicilian Region (37°35′18.0″ N, 12°53′44.0″ E) during the spring-summer 2022 and 2023. In the two experimental years, the plots were located at different points within the farm; both soils were sandy clay loam with discrete content of organic matter and total nitrogen (N); in the second year, the potassium content was slightly higher (Table 1).

Table 1
Physical- chemical proprieties of the experimental site soil.

Parameters	Unit of Measure	Soil 2022	Soil 2023
Sand	%	64	59
Slit	%	13	13
Clay	%	23	28
N total	g kg^{-1}	1.30	1.14
P_2O_5	mg kg^{-1}	21	36
K_2O	mg kg^{-1}	136	211
Organic matter	%	1.46	1.34
pH		7.0	7.4

The experiment was arranged in a randomized block design with three replicates; it was a factorial combination with the growing conditions (*growing conditions, that is soil properties and climate conditions*) as the first factor and the mulching film as the second factor (*Mulching*). In particular, the mulching treatments were: (i) an experimental MaterBi® biodegradable black film, 15 µm thick, (Novamont SpA, Novara, Italy), -BION1; (ii) a commercial black MaterBi® film, 15 µm thick, (Novamont SpA, Novara, Italy), -BION4; (iii) a black low-density polyethylene film, 50 µm thick, -LDPE; (iv) bare soil, -BS. The width of all films was 1 m. The MaterBi® is one of the new prospective biodegradable polymers for use 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 manually placed the day before the transplant was made, in both years on 10 May, with a distance of 1.7 m between the rows and 0.5 m along the row, obtaining a density of approx. 1.2 plants per square meter. The size of each plot (replication) was 1.7 m × 5 m.

2.2. Plant material and crop management

The tested crop was 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 (Vegetables by Bayer, 2024). As for fertilization, only N was added as calcium nitrate (NovaTec® Solub NK-Calcium, Compo-expert) (15.5 %), at a rate of 170 kg ha^{-1}. In both experimental years, irrigation was managed using a drip system, returning 100 % of the evapotranspiration, calculated by the Hargreaves method (Hargreaves and Samani, 1985). 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

Meteorological data were collected by an ATMOS 41 weather station (Meter Group, Pullman, WA, USA) located on-site. The ATMOS 41 measures 12 meteorological variables, including air temperature, relative humidity, vapour pressure, barometric pressure, wind speed and direction, solar radiation, precipitation, and lightning.

The station was connected to a ZL6 datalogger (Meter Group, Pullman, WA, USA), specifically designed to collect data from environmental sensors. The datalogger transfers data to the Cloud via a Subscriber Identity Module. Its operation is powered by six NiMH batteries that are charged by solar cells.

2.4. Soil temperature

Soil temperature was measured at a depth of 5 cm at four-time intervals (12:00 a.m., 6:00 a.m., 12:00 p.m., and 6:00 p.m.) using TEROS 12 probes (Meter Group, Pullman, WA, USA). These probes were connected to the ZL6 data logger (Meter Group, Pullman, WA, USA), and the data were transferred as described in paragraph 2.3. In 2022, the probes were installed on 24 June, while in the second year (2023) a few days after transplanting.

2.5. Vegetative data

At 60 days after transplantation (60 DAT), the following parameters were measured on 15 eggplants for each plot: plant height (cm); root collar diameter (mm); number of leaves (n) and height of first branches per plant (cm).

2.6. Physiological data

The chlorophyll content (μg cm^2) and nitrogen balance index (NBI) were measured using a Dualex Scientific+ (Force A, Orsay, France) portable Chlorophyll meter. Dualex Scientific+ is a multi-function leaf measuring instrument, which can accurately measure the chlorophyll content of leaves, flavonoids and anthocyanin content of leaf surface in real time, and it is a non-destructive measurement. The chlorophyll content was calculated from the far-red light absorbed by chlorophyll and the transmittance of near-infrared light as a reference. The flavonoid content and anthocyanin content were calculated from the different ratios of chlorophyll fluorescence in the epidermis of leaves. The nitrogen balance index NBI is the ratio of chlorophyll and flavonoids. The instrument calibration was completed before the NBI measurement following instructions of the manufacturer. Twenty fully developed leaves were used per each plot. The instrument automatically averaged these readings (Cartelat et al., 2005; Goulas et al., 2004).

2.7. Yield measurements

Harvesting was performed on a sampling area of approximately 4 m^2, corresponding to 5 plants per replicate. During the first year, there were 7 harvests, from 11 June until 31 August, with an 8–10 day interval, only the second harvest was made 30 days after the first. In 2023, there were 7 harvests starting from 19 July until 07 September approximately every 8 days. At each harvest, the number and weight of marketable and non-marketable fruits were determined; the non-marketable fruits were those deformed, rotting or with a colour not typical of the variety. To determine the percentage of fruit dry matter, a representative sample for each treatment and replicate, at the second and third harvests, was weighed and then, oven-dried at 60 °C until a constant weight was reached. For the qualitative analyses, the fruits from the second and third harvests were selected because they were the most representative of commercial production (Consentino et al., 2022).

2.8. Data on the shape and consistency of the fruit

At the second and third harvests, a representative sample of 5 fruits per replicate were used to determine the mean fruit length and width, as well as internal and external firmness. Shape values were expressed in centimeters (cm). Fruit firmness was determined using a digital penetrometer with an 8 mm tip (Turoni srl, Italy), and values were expressed in Newton.

2.9. Analysis of fruit colorimetry

At the third harvest, on a sample of ten marketable fruits per treatment and replication, CIElab colour parameters were determined (L*: brightness, ranging between 0 (black), no reflection, and 100 (white); a* , chromatic parameter ranging between −60 (green) and + 60 (red); b* , chromatic parameter ranging between −60 (blue) and + 60 (yellow) 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*)).

The Browning ΔL 30 min parameters were calculated as the difference between the L value, measured immediately after cutting the fruit and the value of L after 30 min. The parameter Browning Δ l 30 was measured at the centre and periphery of the fruit.

2.10. 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 (HAA) and lipophilic (LAA) 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 (Lichtenthaler and Wellburn, 1983). The samples were extracted with ammoniacal acetone; absorbance of the solution of chlorophyll a, chlorophyll b and carotenoids were 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. (1995) 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. (1999) 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); HAA and LAA were evaluated by the N, N-dimethyl-p-phenylenediamine (DMPD) (Fogliano et al., 1999) and ABTS (2,20-azinobis 3-ethylbenzothiazoline-6-sulfonic acid) (Re et al., 1999) methods, respectively. 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 (NO_3^-) to nitrite on a cadmium reducer (Sah, 1994). The value was expressed as a percentage of nitrogen in nitrate form (N-NO_3) on dry weight. The Kjeldahl method was used to measure the nitrogen concentration in fruits, values were reported in percentages (%) (Consentino et al., 2022).

2.11. Statistical analysis

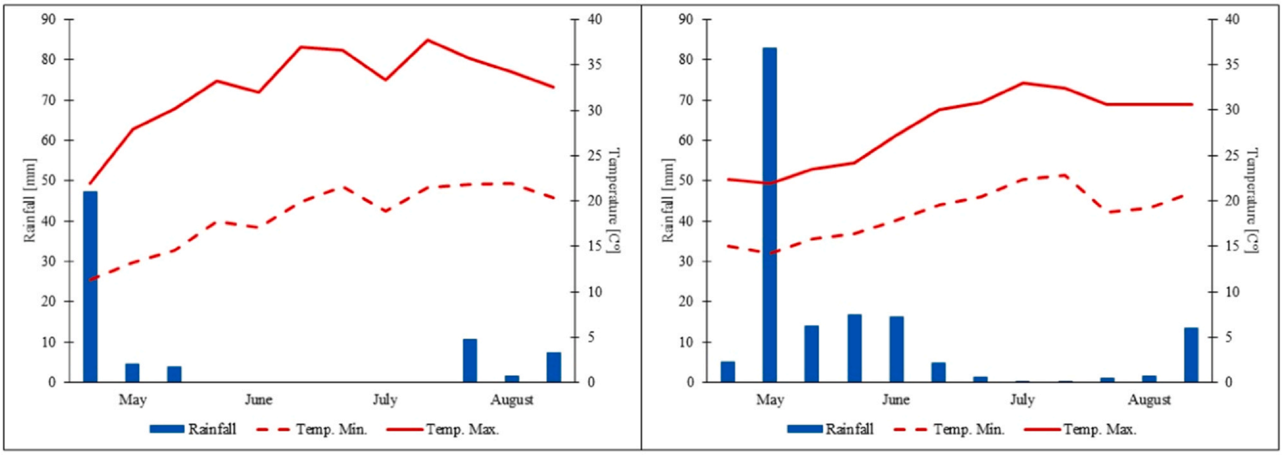
All data were subjected to 2-way analysis of variance (ANOVA) using the MINITAB 19.1.1.0 (State College, PA, USA) software package for Windows. To ensure compliance with ANOVA assumptions, all data were tested for sphericity, normality and variance homogeneity through the Mauchly's test ($\alpha = 0.05$),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

3. Results

3.1. Air temperature and precipitation trends during the two years of study

Total rainfall (TR) recorded at the experimental site during the growing seasons of 2022 and 2023 was 75 mm and 158 mm, respectively, and had a different distribution during the crop cycles. May was the rainiest month in both years (2022 = 75 % of TR; 2023 = 65 % of TR). In 2022, both June and July were dry, whereas only July was dry in 2023.

Regarding air temperatures, in 2022, the maximum values of 30 °C were recorded starting in May, reaching 37 °C in June and 38 °C in July, maintaining an average of 34 °C in August. The lowest minimum



(A) (B)

Fig. 1. Air temperature and precipitation trends during the field trials in both years: 2022 (A) and 2023 (B).

temperatures occurred during the first decade of May (11 ˚C), with a gradual increase in subsequent months, stabilizing at an average minimum temperature of 20 ˚C. In 2023, the maximum temperatures were lower than in the previous year; specifically, maximum temperatures in May ranged from 22–23 ˚C, while in July, the hottest month, maximum temperatures reached 33 ˚C; finally, August maintained maximum temperatures of 31 ˚C throughout the month. Instead, the minimum temperatures were similar to those recorded in 2022 (Fig. 1).

3.2. Soil temperature

Daily soil temperature values monitored during the two experimental years (2022 – 2023) are presented for four-time intervals (12:00 a.m., 6:00 a.m., 12:00 p.m., and 6:00 p.m.) in Figs. 2 and 3. In both years and across all the tested mulch films, the daily minimum and maximum temperatures were recorded at 6:00 a.m. and 6:00 p.m., respectively. In 2022, the BION1 film recorded the highest average maximum temperature throughout the cycle (33.4 ˚C), followed by the LDPE treatments (33.2 ˚C), BS (32.4 ˚C), and BION4 (31.8 ˚C). The lowest average minimum temperature during the entire growing cycle was reported in the BS treatment (25.6 ˚C), followed by BION4 and BION1 (26.2 ˚C) and LDPE (27.2 ˚C).

The soil temperature monitored at 6:00 p.m. in all treatments was consistently above 29 ˚C throughout the growing cycle. Specifically, from the end of June until the third ten-days of July, the highest temperatures were recorded in the BS treatment, with differences of approximately 1.5 ˚C compared to the LDPE treatments. From the third ten-days of July until the end of the growing cycle, the highest soil temperatures were recorded under the BION1 film, with an average difference of about 1 ˚C compared to the LDPE treatments. The plots

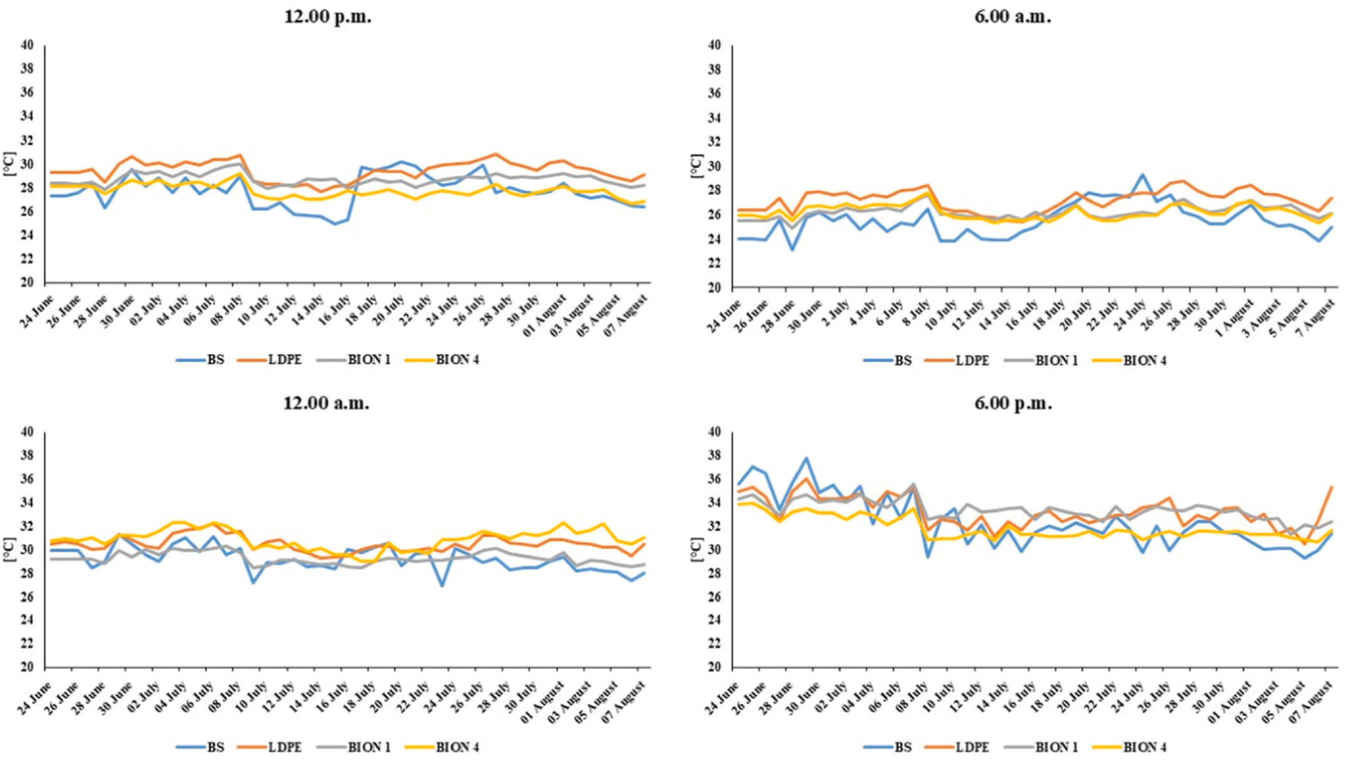


Fig. 2. Daily soil temperatures measured at a depth of 5 cm during 2022 under different mulch films and bare soil. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

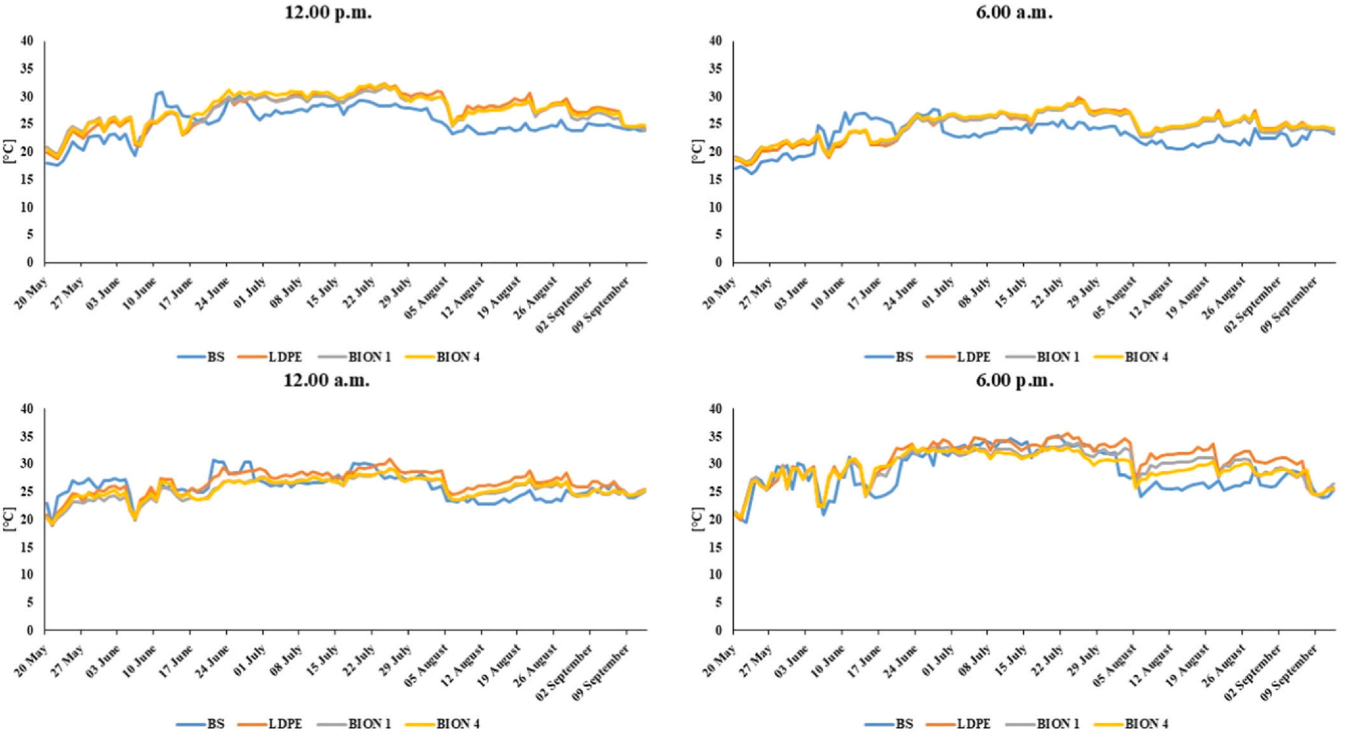


Fig. 3. Daily soil temperatures measured at a depth of 5 cm during 2023 under different mulch films and bare soil. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

mulched with the biodegradable film BION4 generally recorded lower average temperature values compared to the other treatments, with average differences of 0.9 °C, 1.4 °C, and 1.5 °C compared to BS, LDPE and BION1, respectively. Additionally, during the soil temperature monitoring, thermal difference peaks between the BION4 treatment and BS, LDPE, and BION1 were observed, measuring 4.2 °C, 3.6 °C, and 2.6 °C, respectively.

At 6:00 a.m., the highest average temperatures throughout the cycle were recorded in the LDPE treatment, with two temperature peaks of approximately 27.2 °C occurring during the third week of July and the last week of August. The BION4 and BION1 treatments maintained a constant temperature trend of about 26.2 °C throughout the cycle, with a difference of only 0.6 °C between them and the bare soil treatment (25.6 °C). The temperatures under the biodegradable films were on average 1 °C lower than the LDPE treatments. Finally, the average thermal range, calculated between the coldest and warmest temperatures recorded under the films and in the bare soil, were: 5.6 °C for BION4, 6 °C for LDPE, 6.8 °C for BS, and 7.2 °C for BION1 (Fig. 2).

In 2023 (Fig. 3), the average maximum temperature was recorded under the LDPE film (30.8 °C), followed by BION1 (29.8 °C), BION4 (29.4 °C), and bare soil (BS) (28 °C). The average minimum temperature was measured in bare soil (24.2 °C), followed by LDPE and BION1 (24.4 °C) and BION4 (24.7 °C).

From the beginning of the cycle until June 25th, the soil temperature at 6:00 p.m. was on average 28 °C across all the studied treatments. In the second part of the cycle (June 25– September 9, 2023), when soil temperature values were generally higher, the BION4 treatment recorded lower temperatures compared to BION1 (average difference of 0.6 °C with peaks of up to 2.1 °C). Comparing BION4 with LDPE, it was found that the values recorded under the BION4 film were consistently lower (average difference of −1.4 °C and peaks of −3.8 °C). In contrast, comparing BION1 with BS showed higher temperatures (average difference of +1.3 °C and peaks of +5.7 °C). In this case, the greatest differences were observed in August, when the average values measured under the BION4 and BS films were 29 °C and 26 °C, respectively. Similar results were obtained when comparing the biodegradable BION1 film with BS and LDPE.

At 6:00 a.m., the highest average temperature values were recorded under the BION4 treatment (24.7 °C), followed by BION1 and LDPE (24.4 °C) and BS (24.2 °C). The BION4 showed similar temperatures to those with BION1 until June 17; thereafter, the soil mulched with BION4 maintained higher temperatures (average difference of +0.4 °C). Compared with LDPE, from the beginning of the measurement period until the first two weeks of July, the highest temperatures were recorded under the BION4 (average difference of 0.5 °C and peaks of 1.1 °C); thereafter, similar temperature values were recorded. The average thermal excursions were lower compared to the first year of study and were as follows: for BS 3.8 °C; for BION4 4.7 °C; for BION1 5.4 °C; and for LDPE 6.4 °C.

3.3. Vegetative growth parameters and chlorophyll and Nitrogen Balance index

The ANOVA highlighted that both leaf chlorophyll content and NBI were significantly affected by the interaction of growing conditions and mulch type (Table 2), as well as the root collar diameter, number of leaves and height of first branches (Supplementary materials, Table S1). Instead, plant height was affected only by the growing conditions, with the greatest value recorded in the second year in plants grown on the BION4 mulching (Supplementary materials, Table S1). As regards the other vegetative growth parameters measured at 60 days after transplant, the largest collar diameter was recorded in the second year in all mulching treatments, which were not statistically different from the corresponding treatments in 2022, with the exception of for LDPE (Supplementary materials, Fig. S1). Among the mulching treatments, BION1 showed the best performance in both years, while the not-mulched treatments (BS) recorded the lowest collar diameter values (10.64 and 13.29 mm, 2022 and 2023, respectively), that were significantly different from all other treatments and among them (Supplementary materials, Fig. S1). The highest number of leaves was also recorded in 2023 (Supplementary materials, Table S1; Fig. S2) in plants grown on BION1 film (80 leaves), that was significantly different from all other treatments (Fig. S2). BION1–2023 elicited a 13.7 %,

Table 2
Effect of growing conditions (GC) and type of Mulching (M) on Chlorophyll and Nitrogen Balance Index (NBI) at 60 days after transplant (DAT).

Treatments	**Chlorophyll [µg cm^2]**	**NBI**
Growing Conditions (GC)		
2022	33.47 ± 0.80 b	25.91 ± 0.83 b
2023	35.77 ± 1.02 a	28.42 ± 1.24 a
Mulching (M)		
BION1	36.74 ± 1.12 a	29.80 ± 1.69 a
BION4	35.90 ± 0.62 a	28.22 ± 1.15 a
LDPE	33.89 ± 1.92 b	26.27 ± 0.94 ab
BS	31.96 ± 0.61c	24.35 ± 1.64 b
Significance		
Growing Conditions (GC)	0.000	0.018
Mulching (M)	0.000	0.006
GC × M	0.000	0.004

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

13.7 %, 20.9 %, and 57.9 % increase compared to BION1–2022, BION4, LDPE, and BS, respectively (Supplementary materials, Fig. S2). In both years, the lowest number of leaves was observed in the BS treatments (49 in 2022; 52 in 2023), with no statistical differences between the years (Supplementary materials, Fig. S2). The highest value for the height of the first branch was again recorded in 2023 (Table S1; Fig. S3), when the three mulching treatments were not different between them but significantly different from all other treatments. In contrast, in 2022, no significant differences were recorded among the treatments, including BS (Supplementary materials, Fig. S3).

In 2022 and 2023, the values of leaf chlorophyll content ranged from 29.79 to 36.67 µg cm^2 and from 30.74 to 39.23 µg cm^2, respectively; irrespective of mulching, in 2023 leaf chlorophyll content was significantly higher than 2022 (Table 2; Fig. 4). In particular, the highest leaf chlorophyll content was recorded in 2023 in plants grown on the biodegradable film BION1, but it was not statistically different from LDPE in 2023 and BION4 in 2022. The lowest chlorophyll values were observed in LDPE-2022, that were not significantly different from BS-2023 (Fig. 4).

The highest NBI values were measured in 2023 (Table 2; Fig. 7). The trend was similar to that recorded for chlorophyll content. Indeed, BION1 showed the best performance (33.1), and it was not statistically different from the other two mulching treatments in 2023, and from the two biodegradable films in 2022 (Fig. 7). The BS plants showed the lowest NBI values without significant differences between the two years and also compared to LDPE-2022 (Fig. 7).

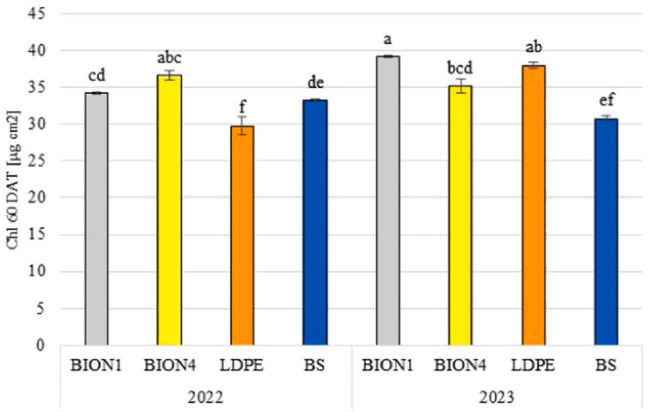


Fig. 4. Influence of the interaction Growing Conditions (2022; 2023) × Mulching on Chlorophyll (Chl). Per each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. DAT: days after transplanting.

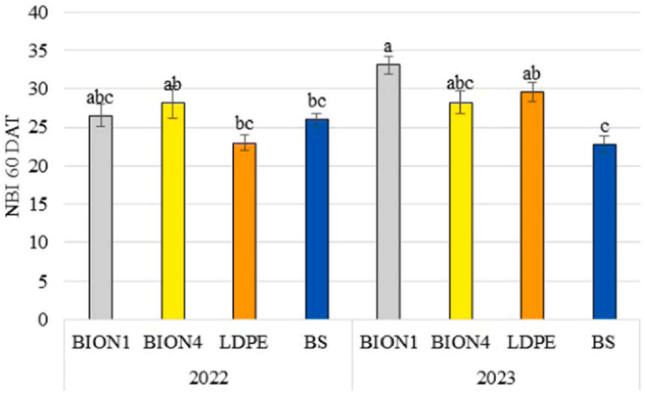


Fig. 5. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Nitrogen Balance Index (NBI). Per each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. DAT: days after transplanting.

3.4. *Yield parameters*

The analysis of variance showed that total yield, marketable yield (MY), non-marketable yield (NMY), and average fruit weight (AMFW) were significantly affected by the interaction GC × M (Table 3).

The best production performances (total and marketable yield) were recorded in the second year of the experiment (Table 3; Fig. 6); specifically, for both parameters the highest and significantly different values were recorded in plants grown on the biodegradable film BION4 in 2023 (95.32 t ha^{-1}; 93.49 t ha^{-1}, respectively), followed by BION1 and LDPE. The lowest yields were recorded in 2022 for plants grown without mulch (33.79 t ha^{-1}; 32.95 t ha^{-1}). The highest non-marketable yield (NMY) was obtained in plants mulched with LDPE in 2023 (1.97 t ha^{-1}), whereas the lowest was found in unmulched plants (BS) without differences between the two years (0.84 t ha^{-1} in 2023; 0.78 t ha^{-1} in 2022) (Fig. 6).

The average weight of eggplant fruits was greater in 2022 (Table 3; Fig. 7), when BION4 showed the best performance that was statically different from all other treatments (Fig. 7). The lowest values were recorded in BS and LDPE in 2023 (Fig. 7).

3.5. *Qualitative Parameters*

3.5.1. *Fruit Shape and Firmness*

The analysis of variance highlighted a significant interaction of the factors, on the length and width, and on the outside and inside firmness of eggplant fruits (Table 4).

The highest value of fruit length was observed in 2022 for BION4 plants (20 cm), that was not statistically different from BION1 (19.90 cm) and BION4 plants (19.03 cm) of 2023 (Fig. 8). However, on average, the values of fruit length in 2023 were higher than 2022 (Table 4; Fig. 8). The smallest fruit lengths were recorded in 2022 for unmulched (BS) and BION1 plants, that were not statistically different. However, these treatments showed the greatest fruit width, but were not statistically different from the other two treatments in the same year (Fig. 8). For this parameter, the lowest values were recorded in fruits of LDPE (4.90 cm) and BS plants (4.83 cm) in 2023 (Fig. 8).

The highest value of outside firmness was reached by LDPE fruits, in both growing conditions, and BS plants in 2023; the lowest outside firmness was observed in the treatments mulched with BION4, BION1,

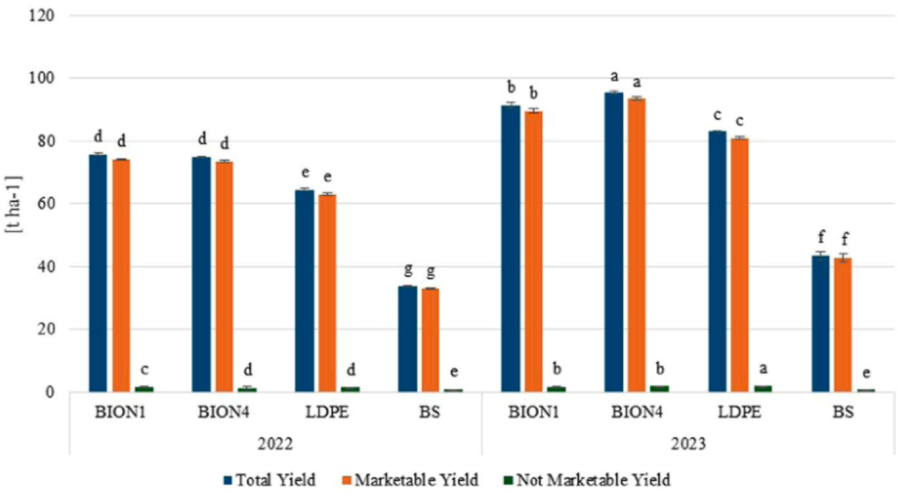


Fig. 6. Influence of the interaction Growing Conditions (2022; 2023) × Mulching on Total Yield (TY), Marketable Yield (MY) and Not Marketable Yield (NMY). Per each data series, values with different letters are significantly different at $p \le 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

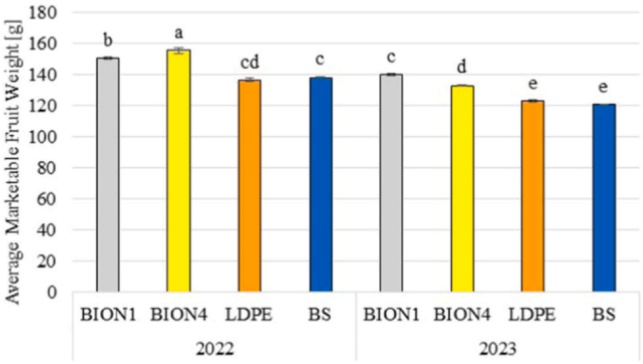


Fig. 7. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Average Marketable Fruit Weight (AMFW). Per each data series, values with different letters are significantly different at $p \le 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

and BS in 2022, as well as in BION4–2023 (Fig. 9). Inside firmness values were again higher in the treatments mulched with LDPE in both years, but these were not significantly different compared to BION1 of both years, and BS-2023 (Fig. 9). The lowest values were recorded in the BS-2022 (11.32 N) that was not different from BION1 and BION4 in 2022 and 2023 (Fig. 9).

3.5.2. *Colour parameters and browning*

The ANOVA about the colour parameters of eggplant fruits highlighted the significant effect of growing conditions on Chroma and brightness (L*), and the effect of the mulching on the HUE parameter; the interaction was never significant (Table 5). Higher values of Chroma and L* were observed in 2022. With regard to the HUE, the two biodegradable films elicited the highest values, while the lowest ones were found in LDPE (0.05) and BS plants (0.09).

The degree of browning (ΔL 30) measured 30 min after the initial reading, both at the center and in the peripheral zone of the pulp, did not show statistical differences between the growing conditions and among the different mulching films used.

3.5.3. *Fruit composition*

Total soluble solids (TSS) and the dry matter (DM) percentage were significantly affected by the interaction (Table 6).

The fruits of BION1–2022 possessed the highest TSS value (5.23°Brix), but this was not statistically different from LDPE and BION4 fruits (5.1 and 4.9°Brix, respectively) in 2023. All other treatments in 2022, as well as BION1–2023, showed the lowest values and did not differ significantly between them (Fig. 10).

As regards the dry matter percentage of fruits, in 2023 higher values were recorded compared to 2022 (Table 6; Fig. 11). The BION1 treatment showed the highest value (8.37 %), but it was not significantly different from LDPE and BS in 2023 (Fig. 11). In contrast, the BION1, LDPE, and BS treatments in 2022 exhibited the lowest values (ranging

Table 3
Effect of Growing Conditions (Y) and type of Mulching (M) on Yield Parameters.

Treatments	Total Yield	Marketable Yield	Not Marketable Yield	AMFW
	[t ha^{-1}]	**[t ha^{-1}]**	**[t ha^{-1}]**	**[g]**
Growing Conditions (GC)				
2022	62.28 ± 5.14 b	60.94 ± 5.05 b	1.33 ± 0.09 b	145.28 ± 2.44 a
2023	78.32 ± 6.20 a	76.73 ± 6.07 a	1.58 ± 0.14 a	129.33 ± 2.33 b
Mulching (M)				
BION1	83.59 ± 3.50 a	81.91 ± 3.46 a	1.68 ± 0.04 ab	145.27 ± 2.38 a
BION4	85.15 ± 4.56 a	83.51 ± 4.47 a	1.63 ± 0.09 b	144.31 ± 5.07 a
LDPE	73.77 ± 4.13 b	72.05 ± 4.02 b	1.71 ± 0.12 a	129.98 ± 3.10 b
BS	38.69 ± 2.26c	37.88 ± 2.28c	0.81 ± 0.02c	129.66 ± 3.89 b
Significance				
Growing Conditions (GC)	0.000	0.000	0.000	0.000
Mulching (M)	0.000	0.000	0.000	0.000
GC × M	0.000	0.000	0.000	0.000

AMFW: Average Marketable Fruit Weight.
BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \le 0.05$, according to Tukey's test.

Table 4
Effect of Growing Conditions (2022; 2023) (GC) and type of Mulching (M) on Fruit Shape (Length and Width) and Firmness (Outside and Inside).

Treatments	Fruit Length [cm]	Fruit Width [cm]	Outside Firmness [N]	Inside Firmness [N]
Growing Conditions (GC)				
2022	17.62 ± 0.46 b	5.75 ± 0.07 a	26.85 ± 1.44 b	14.26 ± 0.85
2023	19.02 ± 0.19 a	5.09 ± 0.09 b	30.61 ± 1.15 a	15.17 ± 0.53
Mulching (M)				
BION1	18.21 ± 0.77 b	5.63 ± 0.15 a	26.90 ± 1.39c	14.55 ± 0.69 b
BION4	19.51 ± 0.33 a	5.40 ± 0.11 ab	23.93 ± 0.44 d	13.20 ± 0.41 b
LDPE	18.15 ± 0.24 bc	5.37 ± 0.22 ab	34.40 ± 0.38 a	17.81 ± 0.54 a
BS	17.42 ± 0.50c	5.29 ± 0.21 b	29.69 ± 1.92 b	13.32 ± 0.54 b
Significance				
Growing Conditions (GC)	0.000	0.000	0.000	0.116
Mulching (M)	0.000	0.050	0.000	0.000
GC × M	0.000	0.016	0.000	0.038

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at p ≤ 0.05, according to Tukey's test.

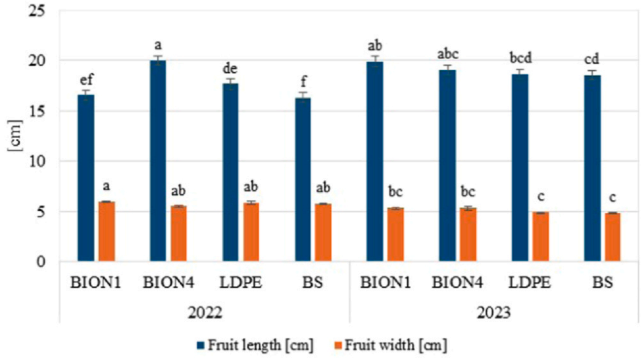


Fig. 8. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Fruit Shape (Length and Width). Per each data series, values with different letters are significantly different at p ≤ 0.05, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

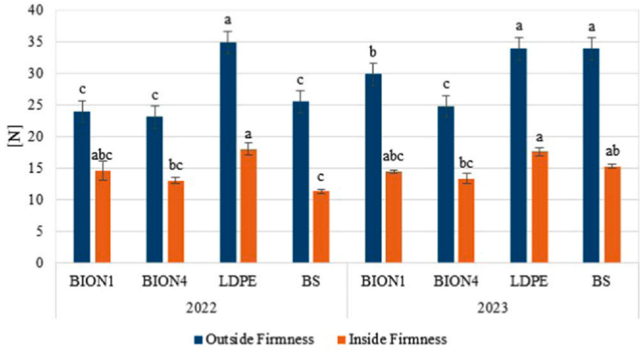


Fig. 9. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Firmness (Outside and Inside). Per each data series, values with different letters are significantly different at p ≤ 0.05, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

from 6.43 % to 6.52 %), with no statistical differences among them (Fig. 11).

3.5.4. *Chlorophyll and nitrate content*

Table 8 shows the results of the ANOVA analysis about the chlorophylls (a, b, and total) and N-NO$_3$ content of eggplant fruits. The interaction growing conditions x mulching was always significant except for N-NO$_3$, that was significantly affected only by year, being higher in 2023 compared to 2022 (Table 7).

The content of chlorophyll a was higher in plants mulched with BION1 (0.032 mg g^{-1} fw) cultivated in 2023, but was only significantly different from BION1–2022. The highest chlorophyll b content was observed in fruits of plants mulched with BION4 (0.026 mg g^{-1} fw) cultivated in 2022, but was significantly different only from BION1–2022 (Fig. 15). The highest total chlorophyll content was measured in the fruits of plants mulched with BION1 (0.057 mg g^{-1} fw) cultivated in 2023, which again was significantly different only from BION1–2022 (Fig. 12).

3.5.5. *Antioxidant activity and bioactive compounds*

Table 8 shows ANOVA of antioxidant activity and bioactive compounds. In particular, the interaction growing conditions × mulching was significant only for ascorbic acid and lipophilic antioxidant activity. Hydrophilic antioxidant activity was not statistical affected by either factor. Total phenol content was affected only by year, being higher in 2022 compared to 2023, while carotenoid content was affected only by mulching: the highest value was measured in BS fruits, while the lowest in plants mulched with BION1, with BION4 and LDPE showing intermediate values (Table 8).

The highest ascorbic acid content was measured in 2022 (more than the double compared to 2023; Table 8), in particular, in the fruits of plants mulched with LDPE (51.88 mg g^{-1} fw), which were not statistically different from the BION4–2022 fruits (42.88 mg g^{-1} fw) (Fig. 13). The lowest values were recorded in 2023 with no significant differences between the treatments (Fig. 13).

As for LAA the best performance was recorded in BION1 (27.45 mM Trolox eq. 100 g^{-1} dw) cultivated in 2022, that was statistically different only from BION4 and BS of the same year, which showed the lowest values (Fig. 14). The other treatments exhibited statistically similar values among each other (Fig. 14).

4. Discussion

Since the 1950s, when farmers started to use plastic films in agriculture (greenhouses and mulching), their use has increased notably as well as the risks of soil pollution due to the release of microparticles, toxins, and carcinogenic phthalate esters that can persist for hundreds of years, representing a significant risk to human health (Tudor et al., 2018). For these reasons, the aim of this study was to investigate whether biodegradable films made from MaterBi® could serve as a valid and eco-sustainable alternative to LDPE mulching films, for cultivation of eggplant, in hot and arid conditions, without adversely affecting yield and some qualitative traits of fruits. Unlike other studies focusing solely on yield and crop quality parameters (Di Miceli et al.,

Table 5
Effect of Growing Conditions (2022; 2023) (GC) and type of Mulching (M) on colour parameters: L* (brightness), C (Chroma), and H (hue angle); and Browning of eggplants fruits.

Treatments	Chroma	HUE	L*	Browning of center ΔL 30 min	Browning outside ΔL 30 min
Growing Conditions (GC)					
2022	5.09 ± 0.19 a	0.12 ± 0.02	25.49 ± 0.20 a	2.92 ± 0.28	3.16 ± 0.42
2023	2.39 ± 0.10 b	0.10 ± 0.01	24.93 ± 0.12 b	2.81 ± 0.24	2.86 ± 0.35
Mulching (M)					
BION1	3.79 ± 0.72	0.18 ± 0.03 a	24.97 ± 0.32	2.64 ± 0.56	2.41 ± 0.38
BION4	3.97 ± 0.64	0.12 ± 0.01 ab	25.44 ± 0.29	3.02 ± 0.34	2.50 ± 0.48
LDPE	3.27 ± 0.57	0.05 ± 0.01 b	25.08 ± 0.22	2.91 ± 0.27	3.56 ± 0.45
BS	3.92 ± 0.59	0.09 ± 0.01 b	25.37 ± 0.17	2.90 ± 0.26	3.56 ± 0.73
Significance					
Growing Conditions (GC)	0.000	0.456	0.030	0.798	0.613
Mulching (M)	0.083	0.000	0.434	0.934	0.339
GC × M	0.531	0.062	0.571	0.845	0.994

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \le 0.05$, according to Tukey's test.

Table 6
Effect of Growing Conditions (GC) and type of Mulching (M) on Total Soluble Solids (TSS) and Dry Matter (DM) of eggplant fruits.

Treatments	TSS [°Brix]	DM [%]
Year (Y)		
2022	4.56 ± 0.13 b	6.75 ± 0.16 b
2023	4.81 ± 0.007 a	8.08 ± 0.06 a
Mulching (M)		
BION1	4.86 ± 0.17 a	7.40 ± 0.43 b
BION4	4.53 ± 0.17 b	7.73 ± 0.06 a
LDPE	4.71 ± 0.18 ab	7.30 ± 0.40 b
BS	4.65 ± 0.09 ab	7.23 ± 0.32 b
Significance		
Growing Conditions (GC)	0.001	0.000
Mulching (M)	0.010	0.000
Y × M	0.000	0.000

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \le 0.05$, according to Tukey's test.

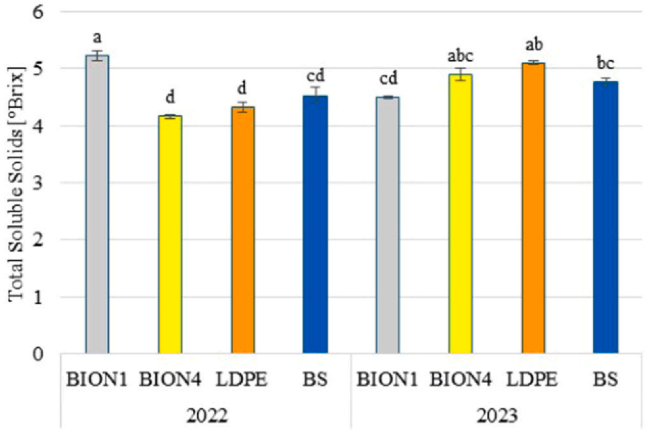


Fig. 10. Influence of the interaction Growing Conditions (2022; 2023) × Mulching on Total Soluble Solids (TSS). Per each data series, values with different letters are significantly different at $p \le 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

2024), our research also examined the morphological and physiological aspects of eggplant plants, as well as soil temperatures under the different mulching films.

In this study, monitoring air temperature allowed for a better understanding of soil temperature variations under different mulching materials. As reported by Melo-Aguilar et al. (2022), the relationship between air and soil temperatures is greatly influenced by changes in ground cover and other factors such as aerodynamic conductance, soil moisture content, and associated changes in soil properties. During the first year of study (2022), maximum temperatures were higher compared to the second year (2023), with average differences of 5.5 °C throughout the growing cycle. The higher air temperatures recorded during the first year were reflected in the increased soil temperatures during the same period, regardless of the type of mulching applied. Soil temperatures, in line with thermal diffusivity analyses, were measured at 5 cm, as the surface soil experiences greater temperature fluctuations than deeper layers (Brunetti et al., 2021). Consistent with Di Mola et al. (2023), we observed an increase in soil temperature in mulched treatments compared to BS (~2 °C) in both years. Our results are also in agreement with Jia et al. (2020), who found that polyethylene films consistently caused an increase in soil temperature compared to biodegradable films. Greater diurnal temperature fluctuations were noted in treatments mulched with LDPE (6.2 °C) and in unmulched treatments (6.8 °C), as also reported by Samphire et al. (2023). Presumably, the differences in diurnal thermal fluctuations between various mulching materials could be attributed to the differing thicknesses of the films (50 vs. 15 μm) and their constituents. LDPE mulching, with a thickness of 50 μm, is designed to be durable, tear-resistant, and effective at warming the soil, thereby contributing to higher soil temperatures. This heating is particularly beneficial during the early stages of the crop growth cycle, when plants are small and require warmer soil conditions.

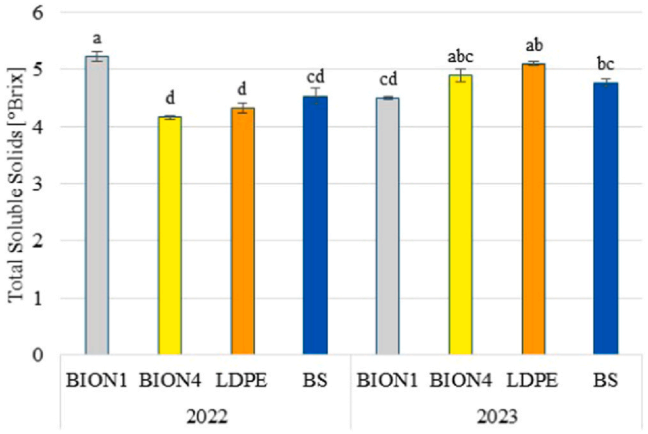


Fig. 11. Influence of the interaction Growing Conditions (2022; 2023) × Mulching on Dry Matter (DM). Per each data series, values with different letters are significantly different at $p \le 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

Table 7
Effect of Growing Conditions (GC) and type of Mulching (M) on Chlorophyll and Nitrate Content of eggplant fruits.

Treatments	Chlorophyll a [mg g^{-1} fw]	Chlorophyll b [mg g^{-1} fw]	Tot. Chlorophyll [mg g^{-1} fw]	N-NO$_3$ [% dw]
Growing Conditions (GC)				
2022	0.019 ± 0.00	0.015 ± 0.00	0.035 ± 0.01	1.80 ± 0.04 b
2023	0.025 ± 0.00	0.016 ± 0.00	0.043 ± 0.00	1.97 ± 0.03 a
Mulching (M)				
BION1	0.019 ± 0.01	0.011 ± 0.00 b	0.033 ± 0.01	1.88 ± 0.04
BION4	0.027 ± 0.00	0.021 ± 0.00 a	0.049 ± 0.00	1.92 ± 0.07
LDPE	0.019 ± 0.00	0.012 ± 0.00 ab	0.032 ± 0.00	1.90 ± 0.06
BS	0.024 ± 0.00	0.019 ± 0.00 ab	0.043 ± 0.00	1.85 ± 0.08
Significance				
Growing Conditions (GC)	0.166	0.689	0.141	0.009
Mulching (M)	0.375	0.015	0.088	0.854
GC × M	0.035	0.020	0.004	0.747

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

Table 8
Effect of Growing Conditions (GC) and type of Mulching (M) on Ascorbic acid, Carotenoids, Hydrophilic Antioxidant Activity (HAA), Lipophilic Antioxidant Activity (LAA), Total Phenols.

Treatments	Ascorbic acid [mg g^{-1} fw]	Carotenoids [mg g^{-1} fw]	HAA [mM AA eq .100 g^{-1} dw]	LAA [mM Trolox eq. 100 g^{-1} dw]	Total Phenols [mg GA g^{-1} dw]
Growing Conditions (GC)					
2022	39.57 ± 3.22 a	0.025 ± 0.00	5.04 ± 0.38	20.32 ± 1.67 b	2.89 ± 0.29 a
2023	16.32 ± 0.934 b	0.028 ± 0.00	5.10 ± 0.31	24.50 ± 0.26 a	1.35 ± 0.10 b
Mulching (M)					
BION1	25.17 ± 4.69 ab	0.022 ± 0.00 b	5.19 ± 0.71	25.88 ± 0.86 a	2.58 ± 0.55
BION4	29.01 ± 6.48 ab	0.028 ± 0.00 ab	5.30 ± 0.42	20.74 ± 2.17 b	2.22 ± 0.45
LDPE	33.58 ± 8.49 a	0.023 ± 0.00 ab	4.73 ± 0.51	22.38 ± 1.49 ab	2.12 ± 0.49
BS	24.04 ± 3.22 b	0.032 ± 0.00 a	5.07 ± 0.29	20.62 ± 2.17 b	1.55 ± 0.17
Significance					
Growing Conditions (GC)	0.000	0.257	0.898	0.004	0.000
Mulching (M)	0.044	0.033	0.833	0.028	0.103
GC × M	0.005	0.764	0.070	0.020	0.350

BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil. Within each column values (means ± standard error) with different letters are significantly different at $p \leq 0.05$, according to Tukey's test.

In contrast, biodegradable mulches, with a thickness of 15 µm, are thinner to balance tear resistance and biodegradable capacity (Bianchini et al., 2022). This thinner design may also facilitate more rapid heat exchange between the soil and the atmosphere, resulting in slightly lower average soil temperatures (Sellami et al., 2024).

As expected, mulching resulted in improved growth parameters for eggplant plants. Notably, these improvements were more pronounced during the second year of the study, presumably due to the lower ambient air temperatures that also affected soil temperature. It has been shown that gene expression in seedlings is strongly influenced by root temperature (González-García et al., 2023). These genes are related to auxin signaling and are downregulated in plants grown at soil temperatures exceeding 32 °C (Stortenbeker and Bemer, 2018). Auxin plays an essential role in shoot growth, biomass production (Tivendale and Millar, 2022), and thermomorphogenic responses induced by thermal stress, including hypocotyl elongation and leaf hyponasty (Gray et al., 1998; Küpers et al., 2020). Thus, a decrease in auxin signaling could partially explain the observed decline in growth (collar diameter, leaf number, and height of the first fertile branch) in eggplant plants cultivated during the first year of the study. Furthermore, one of the main

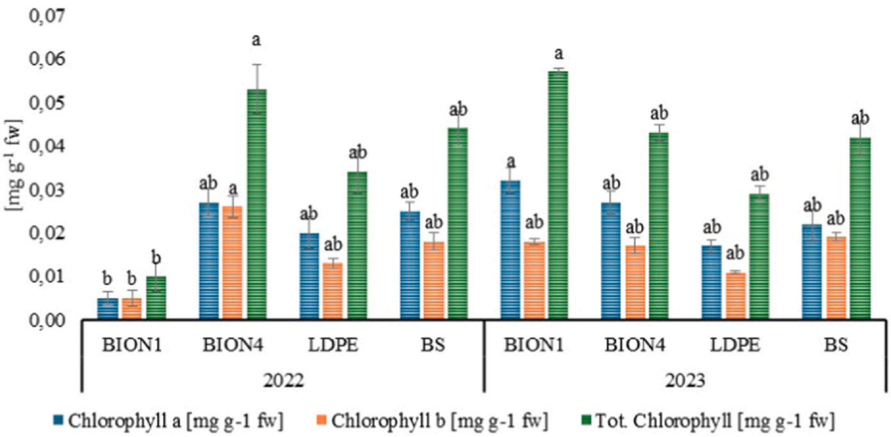


Fig. 12. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Chlorophyll a, b and Total. Per each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

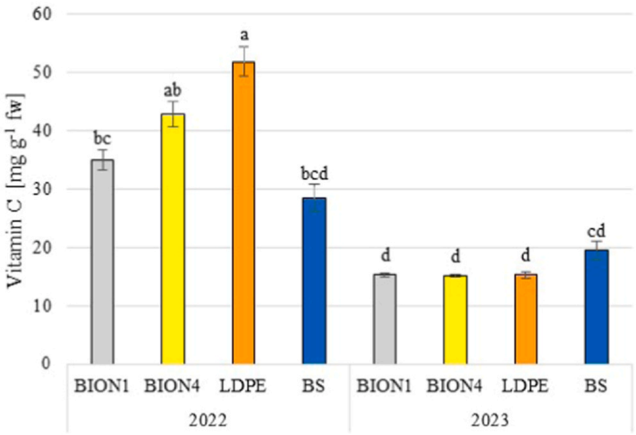


Fig. 13. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Ascorbic acid. Per each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

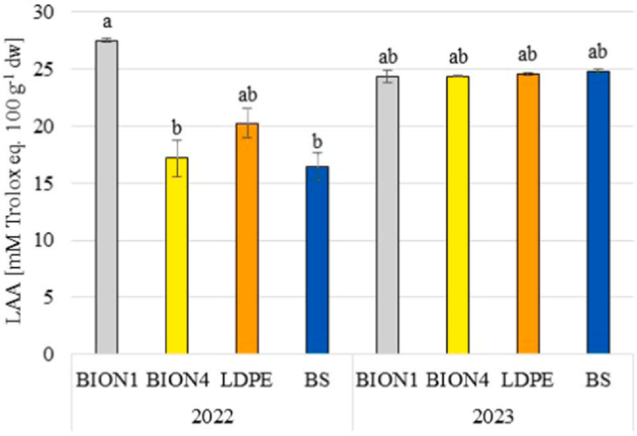


Fig. 14. Influence of the interaction of Growing Conditions (2022; 2023) × Mulching on Lipophilic Antioxidant Activity (LAA). Per each data series, values with different letters are significantly different at $p \leq 0.05$, according to Tukey's test. Bars represent means ± standard error. BION1: experimental MaterBi®; BION4: commercial MaterBi®; LDPE: Low Density Polyethylene; BS: bare soil.

limiting factors influencing plant growth is the reduction in nutrient availability caused by high soil temperatures (Pregitzer and King, 2005; Onwuka and Mang, 2018).

The chlorophyll content and NBI measured in eggplant leaves were higher during the second year of the study and in plants mulched with MaterBi® films. Regarding chlorophyll content, our results are consistent with studies by Verdial et al. (2001), Abu-Rayyan et al., 2024, and Samphire et al. (2023), which reported higher leaf N content in plants mulched with biodegradable films. These authors suggest that the increased leaf N content was attributed to lower soil temperatures. The NBI is defined as the ratio of chlorophyll to epidermal flavonoids and is used to assess N nutrition in precision agriculture (Cartelat et al., 2005), as it is considered an effective estimator of leaf N content (Cerovic et al., 2015). In our study, the NBI followed a similar trend to that of chlorophyll content, showing a higher index value in mulched plants compared to BS.

The increased size of commercial fruits can be attributed to a wider harvest interval (12 days) compared to the harvest interval (7 days) established in 2023. The timing of the harvests varied between the two years due to air temperatures; in fact, weekly harvesting was not feasible when there were few ripe fruits. As reported by several authors (Alam and Salimullah, 2021; Mohideen et al., 1977; Di Miceli et al., 2024), air temperatures exceeding 35 °C compromise flowering, fruit set, and overall productivity in eggplant plants. Generally, mulching led to an increase in yield compared to unmulched soil, with a more pronounced effect in plants mulched with BION4 during 2023. The yield increase obtained with the application of biodegradable films has been reported in various crops, such as tomatoes (Di Mola et al., 2023, b; Abduwaiti et al., 2021; Jia et al., 2020), eggplant (Di Miceli et al., 2024), and melons (Sellami et al., 2024). From our observations, the differing productive behaviour can be attributed to the lower temperatures recorded under the BION4 film compared to those under LDPE films, as well as the more moderate daily thermal fluctuations compared to bare soil. In eggplant, seed production is a negative event that can compromise overall yield; in environments characterized by high temperatures, harvesting often occurs when fruits are immature and before complete development (Gajewski and Arasimowicz, 2004; Alam and Salimullah, 2021). In addition to the fraction of fruits with a high seed content, the non-commercial yield was characterized by fruits with undesirable colour, poor texture, and a pronounced bitter flavour. In our study, contrary to the findings of Di Miceli et al. (2024), which reported a higher non-commercial yield in unmulched eggplant plants, these undesirable characteristics were more prevalent in fruits from plants mulched with LDPE and BION1, where higher soil temperatures were recorded.

Fruit development in plants is typically divided into two phases: cell division, which occurs primarily at the onset of fruit development, followed by cell expansion until the final size and shape of the fruit are established (Gillaspy et al., 1993; Zhang et al., 2006; Xiao et al., 2009). Many studies have focused on these two phases (Baldazzi et al., 2019; Mauxion et al., 2021; Pang et al., 2024), with little emphasis on the environmental effects on final fruit size. In our study, we observed different patterns regarding fruit length and width across the two years. Our results suggest that the phases of cell division and expansion are not only linked to water and nutritional status (Díaz-Pérez and Eaton, 2015), but also to the microclimatic conditions surrounding the plant.

Fruit firmness is a significant quality parameter linked to intrinsic fruit characteristics (size, maturity stage, cuticle thickness, and natural waxes on the fruit surface) (Yan et al., 2024), as well as environmental factors (light, temperature, and humidity), genetic and physiological traits, cultivation practices (Sams, 1999), and post-harvest conditions (Aurand et al., 2012). In our study, both inside and outside firmness was greater in fruits from LDPE-mulched plants in both years, aligning with the findings of Di Miceli et al. (2024), and Moreno et al. (2014), but contradicting other studies that focused on biodegradable mulching. For instance, Di Mola et al. (2023) reported higher firmness in industry tomatoes grown with biodegradable mulch and in the absence of mulch. We can hypothesize that the greater firmness of the fruits is attributable to the lower average weight (smaller fruits) and lower percentage of dry matter in the fruits.

The colour of the eggplant fruit's epicarp is another important parameter, especially for products intended for fresh consumption (Ilic et al., 2022). Colour is associated not only with visual preferences but also with nutritional, health-related, and taste values (Mennella et al., 2012). Both Chroma and L values were higher during the second year and were not influenced by mulching, unlike HUE, which was greater in fruits from plants mulched with BION1 and BION4. As noted by Radicetti et al. (2016), variations in eggplant fruit colour can depend on the proportion of chlorophyll and anthocyanins, and is influenced by agricultural practices and harvest timing; therefore, caution should be exercised in interpreting these data.

To the best of our knowledge, the improvement of DM content due to the application of biodegradable films has only been reported in melon by Sellami et al. (2024). In our study, both total TSS and DM content were influenced by mulching, indicating that °Brix and % DM in eggplant are not solely determined by water deficit (Martins et al., 2024), irrigation levels (Çolak et al., 2018), soil management practices

(Radicetti et al., 2016), or genotype (Salas et al., 2020). Moreover, the observed range of TSS values, fluctuating between 5.23 and 4.16°Brix, was significantly higher than those reported in previous studies. This, we hypothesize that, similar to other quality parameters, environmental factors such as air and soil temperature, along with the thickness of the mulching film, may play a crucial role in shaping these characteristics.

Nitrogen is a constituent of chlorophyll; therefore, the differences in chlorophyll content in fruits can largely be attributed to the availability of this element (Radicetti et al., 2016). Over the two years of the study, the chlorophyll content in the fruits showed a consistent pattern only in non-mulched plants and those mulched with LDPE, further confirming the key role that biodegradable films play in regulating soil temperatures and thus in the bioavailability of this element. Indeed, as reported by Wang et al. (2022) and Bandopadhyay et al. (2018), biodegradable mulching influences water content, temperature, microbial and enzymatic activity, as well as soil fertility.

The evaluation of ascorbic acid content is a crucial parameter for vegetables intended for fresh consumption, as it helps prevent browning of the fruit after cutting. In our study, both the year and the type of mulching significantly influenced the ascorbic acid content in eggplant fruits. The highest values were recorded during the first year of the study and in plants mulched with LDPE, consistent with the findings of Di Miceli et al. (2024). As observed in tomatoes, it can be inferred that the increased solar radiation (Gautier et al., 2009) and greater water availability (Rashmi and Negi, 2020) associated with the LDPE film may contribute to higher accumulation of ascorbic acid.

Eggplant fruits are known for their low caloric content, high fiber and K content, and significant antioxidant activity (San José et al., 2014). Compared to other Solanaceae, they are low in carotenoids (Mishiba et al., 2020). The antioxidant activity of eggplant fruits primarily depends on the content of anthocyanins and phenolic acids (Liu et al., 2018). In particular, the BION1 film stood out, aligning with the results obtained by Di Miceli et al. (2024).

5. Conclusion

The results of this study on the application of different biodegradable films revealed new agronomic aspects regarding eggplant. Monitoring soil temperature at four different times of the day allowed for a better understanding of daily thermal fluctuations and temperature trends throughout the growth cycle. In particular, our study, demonstrated that MaterBi® films not only affect yield and certain quality aspects but also impact growth and key physiological parameters of eggplant. Soil-biodegradable mulch films increased total yield by approximately 46% compared to BS and reduced the percentage of non-commercial fruits compared to LDPE and bare soil. Among the quality parameters, improvements in dry matter, ascorbic acid, and lipophilic antioxidant activity were observed, indicating that not only genotype selection or common agronomic techniques (irrigation, fertilization) can enhance the nutraceutical parameters of eggplant fruits. The evidence from our results suggests that MaterBi® films, by modulating soil temperature, should be considered, especially in environments where the effects of rising ambient temperatures are more pronounced. Therefore, while further research is certainly needed to investigate the interaction between environment, cultivation technique, mulching, and species, these findings suggest that a wider adoption of biodegradable films may be advisable. Furthermore, assistance in moving beyond the use of non-biodegradable polyethylene mulch films could be provided by policy tools such as agri-environmental measures or payment for ecosystem services.

CRediT authorship contribution statement

Federica Alaimo: Visualization, Data curation. **Ida Di Mola:** Writing – original draft, Data curation, Conceptualization. **Noemi Tortorici:** Visualization, Data curation. **Nicolò Iacuzzi:** Writing – original draft, Resources, Investigation, Data curation, Conceptualization. **Teresa Tuttolomondo:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization. **Mauro Mori:** Writing – review & editing, Supervision, Funding acquisition, Data curation, Conceptualization. **Mauro Sarno:** Writing – review & editing, Visualization, Data curation. **Eugenio Cozzolino:** Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ijagro.2024.100025.

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