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Effect of Biodegradable Mulch and Different Synthetic Mulches on Growth and Yield of Field-Grown Small-Fruited Tomato (*Lycopersicon esculentum* Mill.)

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Abstract: Mulching is a widely adopted practice in vegetable cultivation globally. This technique employs various plastic materials, such as polyethylene (PE) film or polypropylene (PP) nonwoven fabric, with an increasing trend toward the use of biodegradable materials. Between 2014 and 2016, field experiments were conducted to evaluate the performance of the small-fruited tomato Intrigo F1 cultivated using synthetic mulches. The trials, designed as single-factor experiments employing a randomized block layout with three replicates, assessed plant morphological traits, yield, and the biological value of the tomato fruits. Weather conditions and the type of mulch applied had a pronounced influence on the quality of tomato plants and yield. Compared to the control, the use of black, red, and aluminum PE films and brown PP resulted in a 7.2% increase in plant height. All mulching treatments, except white film, increased the lateral spread of the plants by an average of 24.2%. Plants cultivated on red PE film exhibited a 26.4% increase in leaf count with respect to the control. Mulched treatments achieved an average increase of 19.6% in marketable yield. The highest marketable fruit yield was recorded with black nonwoven fabric mulch. Mulching had a significant effect on the chemical composition of tomato fruits. Fruits on biodegradable foil had the most potassium, lycopene, and polyphenols.

Keywords: black polyethylene film; white polyethylene film; red polyethylene film; aluminum-coated polyethylene film; polypropylene nonwoven fabric; marketable yield; lycopene; phenolic; carotenoids; vitamin C

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1. Introduction

The tomato (*Solanum lycopersicum* Mill.), a member of the nightshade family, stands as a paramount horticultural species globally. Its cultivation is notably facile, and the plethora of thousands of registered varieties facilitates its adaptability for commercial cultivation by both smallholder and large-scale producers alike. World tomato production is 192.3 million tons. This species is cultivated on over 5.4 million ha globally and the average yield is 35.5 t·ha^{-1}. In Europe, it occupies 395.5 thousand ha, the production is about 21.5 million tons, and the average yield is 54.3 t·ha^{-1}. In Poland, it is cultivated on 8.5 thousand ha, the harvest is around 0.9 million tons, and the yield is 103.9 t·ha^{-1} [1]. The tomato's diverse applications have led to a classification system that distinguishes between varieties destined for fresh market consumption and those intended for processing purposes. Varieties earmarked for direct consumption are cultivated in both protected environments, such as greenhouses, and in open-field settings.

Mulching the soil is a cultivation practice widely used for various reasons, especially on a large scale in vegetable production. Synthetic mulching has been popular since the 1950s and has proven to be very effective [2]. At the beginning of the 21st century, synthetic mulches were used on nearly 13 million hectares worldwide. In 2017, Mormile et al. [3] estimated that the total global area of agricultural land mulched was about 18 million hectares. The benefits of mulching include increased soil temperature and moisture, reduced nitrogen leaching losses, faster fruit ripening, increased yields, prevention of soil erosion, and weed suppression, which in turn reduces herbicide use [4–6].

In temperate climates, synthetic mulches play a significant role in enhancing growth conditions for thermophilic species belonging to the *Solanaceae* and *Cucurbitaceae* families. The effectiveness of such mulches is influenced by the color of the mulch. Mulches also contribute to optimizing the radiation balance, which depends on the type of material used. They can transmit, absorb, or reflect portions of solar radiation, directly influencing above-ground plant growth. Kader et al. [7] confirmed that mulching is an effective water conservation technique, reducing soil evaporation. Furthermore, Amare and Desta [8] emphasized that the color of the mulch significantly affects soil moisture levels and its water retention capacity. The color of the (mulch) mulching film determines its photoselective properties, thereby influencing the microclimate surrounding the cultivated plants. Additionally, it impacts soil temperature both at and below the surface. Bucki and Siwek [9] reported that in temperate climates, black polyethylene PE film raises daytime soil temperature by an average of 3–4 °C, while polypropylene (PP) fabric achieves an increase of 1–2 °C. Amare and Desta [8] observed that black and blue polyethylene (PE) films tend to increase soil temperature, whereas light-colored and white films reduce it. The factors mentioned above directly influence the above-ground growth of plants. Experimental studies have demonstrated that tomato plants cultivated on black or white mulching films exhibit an increased number of leaves and longer stems compared to those grown on red or silver mulching films [10]. Mutoro [11] found that using white mulching film for tomatoes enhanced plant height and the number of stems. Research conducted by Bhujbal et al. [12] revealed that specific mulch colors, such as black on silver film, silver on black film, and transparent film, promote flowering, fruiting, and yield while simultaneously reducing the incidence of pest-induced plant diseases. The accelerated development of the above-ground parts of vegetables grown with mulching directly translates into improved yields, a trend observed across multiple species and climate zones. Adamczewska-Sowińska et al. [13] demonstrated that the use of black PE film mulch significantly increased eggplant yield in temperate climates.

The growing issue of environmental pollution caused by synthetic materials has necessitated increased interest in biodegradable alternatives, such as those derived from corn starch and biodegradable polymers. Under aerobic conditions, these mulches are decomposed by soil microorganisms into carbon dioxide and water. Sękara et al. [14] demonstrated that tomatoes cultivated using biodegradable mulch exhibited superior quality and health compared to those grown with black PE film. Additionally, they noted that biodegradable mulches do not require manual removal from the field after the cultivation cycle. Research conducted by Gabryś et al. [15] established that the use of biodegradable viscose fabric mulch in tomato cultivation provided optimal thermal and water conditions while effectively suppressing weed growth.

The effect of mulching on the chemical composition of the edible portions of vegetables remains inconclusive. Nevertheless, certain studies suggest that the type and color of mulch may enhance the biological value of the harvested yield.

The objective of the study was to assess the response of small-fruited tomato plants to mulching with synthetic materials and biodegradable mulch. It was hypothesized that, under temperate climate conditions, the applied mulches would have a positive impact on the growth, yield, and nutritional value of the tomato fruits. The study aimed to evaluate the impact of various synthetic mulching materials on the growth, yield, and biological value of the tall-growing small-fruited tomato variety Intrigo F1.

2. Materials and Methods

The field experiment was conducted over the period of 2014–2016 at the Vegetable and Ornamental Plant Research and Teaching Station Psary of the Department of Horticulture, Wroclaw University of Environmental and Life Sciences (51°19′08″ N, 17°03′37″ E). The experimental design followed a randomized block layout with three replications. The following synthetic mulches were evaluated: PE films, 0.05 mm thick, in black (PE black) and white (PE white), as well as red PE film (PE red) and aluminum-coated PE film (PE alu) with a thickness of 0.025 mm. Additionally, PP nonwoven fabric with a weight of 50 g m^{-2} was tested in black (PP black) and brown (PP brown). A black biodegradable film, BioAgri (Fbio (I), Italy), 0.025 mm thick, was included. This film is manufactured from Mater-Bi®, a bioplastic material derived from complexed starch and biodegradable polyesters, and it is certified as biodegradable and compostable in compliance with European Standard EN 13,432 and American Standard ASTM D6400 [16]. Control plots (Control) consisted of unmulched soil. The films and nonwoven fabrics were laid out in 2.5-m-wide strips four days before transplanting the tomato plants into the field. Each experimental plot measured 3.75 m^2, and the plants were cultivated at a spacing of 80 × 50 cm.

The experiments were conducted on degraded black soil made from light clay with weak sandy on medium clay subsoil material with a humus content of 1.8% and classified as soil quality class IIIa (Polish Soil Classification System) [17]. In the autumn, prior to the experiments, deep pre-winter plowing was performed, followed in spring by cultivator tillage and soil loosening with a rotary tiller. Before establishing each experiment, chemical soil analysis was conducted in autumn.

The soil pH ranged from 7.2 to 7.9, with salinity between 96 and 240 $\mu S \cdot cm^{-1}$. The macronutrient levels in the soil were adjusted to optimal values: 70 mg $P \cdot dm^{-3}$, 200 mg $K \cdot dm^{-3}$, and 65 mg $Mg \cdot dm^{-3}$. Fertilization included the application of granular triple superphosphate and potassium sulfate. In spring, prior to transplanting the tomato plants, nitrogen was applied at a rate of 150 $kg \cdot ha^{-1}$ in the form of ammonium nitrate.

Tomato seeds were sown in a greenhouse on April 10th into seed trays filled with a peat substrate. After the development of cotyledons and the appearance of the first true leaf, the seedlings were transplanted into pots with a 10 cm diameter between 27th and 29th April. To harden the plants, they were moved to an unheated plastic tunnel 10 days prior to planting. The tomato seedlings were transplanted into the field on the following dates: 26 May 2014, 25 May 2015, and 29 May 2016. The plants were cultivated with 2-m-high wooden stakes and conducted using a two-stem system.

Throughout the vegetative period, tomato plants were irrigated as required, with a single water application rate of 30 mm per irrigation. Toward the conclusion of the seedling production phase and during field cultivation, chemical treatments were systematically applied to protect the plants from bacterial and fungal diseases. The plant protection procedures adhered to the guidelines outlined in the current Vegetable Plant Protection Program. Lateral shoots and lower leaves were routinely pruned to maintain plant structure and health. At the end of August, plant topping was performed by removing the apical section of the main stem. This operation ensured that two to three leaves were retained above the final, sixth fully developed inflorescence on each of the two conducted stems.

In 2014, the harvests were carried out on 1, 6, 18, and 25 August and 8 September. In 2015, harvesting took place at weekly intervals from 3 August to 5 October, while in 2016, harvesting occurred from 2 August to 12 September. Harvesting was performed when nearly all fruits within a cluster (except for the last 3–5 fruits) had reached full ripeness. The yields were categorized as total yield, marketable yield, and early marketable yield. The marketable yield consisted of ripe, uniformly colored, healthy fruits, while the early marketable yield included fruits from the first three harvests. The average number of fruits and the average fruit weight (g) from each cluster weighted for each harvest were assessed.

Biometric measurements of the plants were conducted during the first ten days of July (1–10 July) and August (1–10 August). Two plants were randomly selected from each plot for measurement. The following parameters were recorded: plant height from the base of the stem to the apex (cm), stem diameter at 1 cm above the soil surface (mm), the lateral spread of the plant at mid-height (cm), and the number of leaves.

At the end of August, during the full vegetative period, tomato fruit samples were collected for chemical analysis. A total of 30 mature fruits from each plot were selected for this purpose. The samples were analyzed for their content of dry matter, mineral nutrients, and organic compound composition.

2.1. Chemical Analysis Methodology

The dry matter content in tomato fruits was determined using the oven-drying method, with samples dried at 105 °C. Phosphorus and magnesium were quantified using the colorimetric method in dry matter (spectrophotometer type 102). The phosphorus content was measured using a spectrophotometer set to a factor of 1.36 and a wavelength of 470 nm, while magnesium was measured at a wavelength of 555 nm with a factor of 0.33. Potassium and calcium were analyzed by flame photometry in dry matter (flame photometer Carl Zeiss, Jena, Germany), and nitrate content was determined using potentiometric methods in fresh matter (ionometer Thermo Orion 5 Star, USA). Vitamin C content was analyzed using Tillmann's method in fresh matter (PN-90/A-75101/11), while total and reducing sugars were measured using the Lane–Eynon method in fresh matter. Polyphenols were determined using the Folin–Ciocalteu method in fresh matter. Total carotenoid content was assessed using the colorimetric method in fresh matter. Absorbance was measured using a spectrophotometer against a blank (80% acetone) at wavelengths of 663, 645, and 470 nm for a single sample. Lycopene content was determined using the Fish method, with absorbance measured at a wavelength of 503 nm against the blank (hexane). Polyphenols and lycopene were measured using a Spectroquant Pharo 100 Merck spectrophotometer (Switzerland). Antioxidant activity was evaluated using the DPPH method in fresh matter.

2.2. Weather Conditions

The tomato is a thermophilic vegetable, and as such, the success of its cultivation is largely dependent on temperature fluctuations as well as the amount of precipitation during the growing season. While it can be grown in a variety of climatic conditions, the optimal temperature for most varieties ranges from 21 to 24 °C. Boote et al. [18] indicated that the optimal lower temperature is 22 °C and the optimal upper temperature is 28 °C. Tomato tissues are susceptible to damage when temperatures fall below 10 °C or exceed 38 °C [19,20]. Ayankojo and Morgan [21] highlighted that mitigating heat stress caused by high temperatures in warm climates contributes to improved tomato yields. Throughout the course of the study in a temperate climate, the weather conditions varied across the years.

At the time of tomato seedling planting, the average temperatures were 17.3 °C, 14.0 °C, and 20.9 °C. During this period, precipitation was highly variable. In 2014, the total rainfall amounted to 42.8 mm; in 2015, it amounted to 0.5 mm; and in 2016, no precipitation occurred. In 2014, the conditions during planting were favorable for the rapid establishment of the plants. The average temperature in July was 2.7 °C higher than the long-term mean for the month. Rainfall during June and July was significantly low, constituting only 34.2% and 55.3%, respectively, of the long-term average for these months. Water deficits were compensated through irrigation. The low temperatures observed from 11 August to 20 August (average 17.4 °C) and from 21 August to 31 August (average 15.9 °C), along with substantial rainfall during this period, contributed to the onset of *Phytophthora infestans* (potato blight) on the tomato plants. The climatic conditions in 2014 were the least conducive to tomato yield.

In 2015, low air temperatures (average 14.0 °C) immediately following transplanting inhibited tomato growth. However, during the subsequent two months, temperatures were optimal for flowering, fruit set, and subsequent fruit development. The precipitation in July and August was insufficient, resulting in water deficits that were addressed through irrigation. The average temperature in August was 6.7 °C higher than the long-term mean for the month. Elevated temperatures and low humidity in August and September promoted plant health, and no symptoms of potato blight were observed. The final fruit harvest occurred in the first 10 days of October. This year represented the most favorable environmental conditions for tomato development and yield.

Between 21 May and 31 May and from 1 June to 10 June 2016, the air temperature was higher by 6.7 °C and 4.1 °C, respectively, compared to the long-term averages for these months, while rainfall was either absent or minimal. Following transplanting, the seedlings required intensive irrigation. In the subsequent two months, temperatures remained above the long-term averages (averaging 21.5 and 20.5 °C). Intense rainfall during the second 10 days of July (70.5 mm) favored vegetative growth. However, the precipitation in August and the first 10 days of September was low, while the average temperature at the beginning of September was 21.2 °C. These conditions were optimal for the maturation of tomato fruits.

2.3. Experimental Design and Statistical Analyses

The results obtained in the experiment were subjected to statistical analysis using analysis of variance (ANOVA/MANOVA) in the Statistica 13 software package. The experiment was two-factor. Years of study were considered as the first factor and the type of mulches was the second factor. The statistical analysis also included the interaction of years and type of mulch. Confidence intervals were calculated using Tukey's test at a significance level of $\alpha = 0.05$.

3. Results and Discussion

3.1. Morphological Characteristics

The analysis of the study results revealed that both the climatic conditions and the type of synthetic mulch applied significantly influenced the morphological characteristics of the tomato plants of the Intrigo F1 variety (Figures 1–4). During the measurements conducted in July, significant differences were observed in plant height and lateral spread across the study years (Table 1), as well as in plant height in relation to the type of mulch used (Figure 5). By contrast, in August, only stem diameter did not show significant variation between the years. The tallest plants with the greatest lateral spread were recorded in 2015, both during the first and second measurement periods (Table 1, Figures 1 and 3). In the August measurement, the height of the plants grown in 2016 was comparable to that of the 2015 plants, while the plants from 2014 exhibited the greatest leaf development.

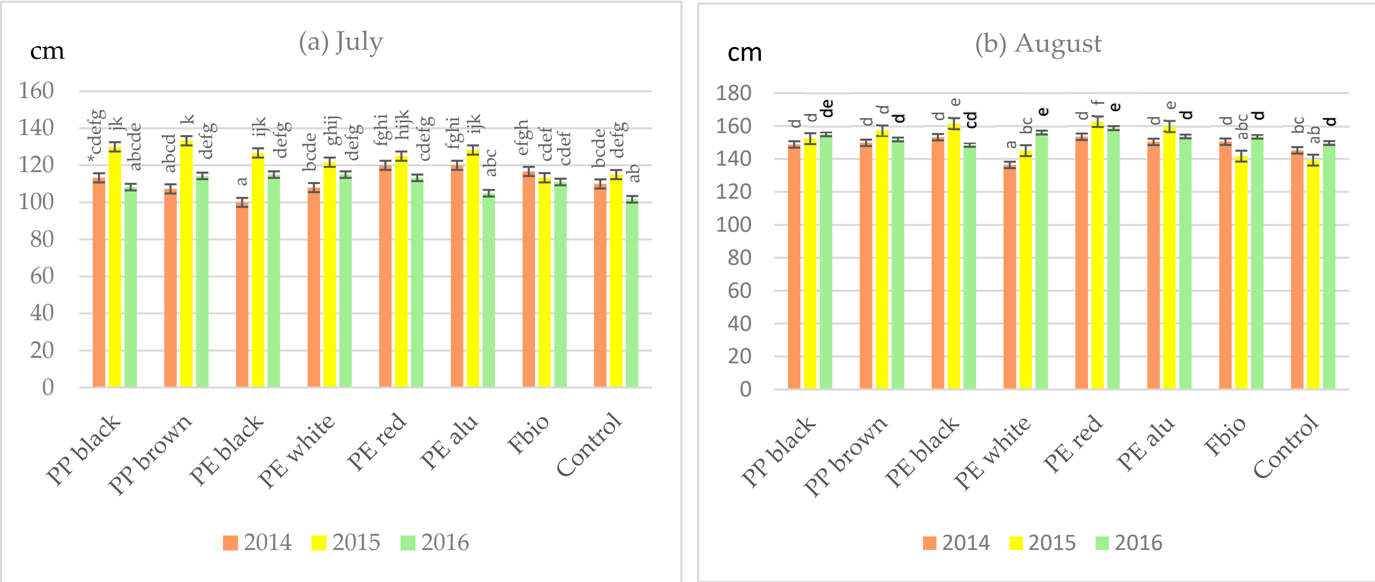

Figure 1. Tomato plant height depending on the type of mulch in 2014–2016 (cm). * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

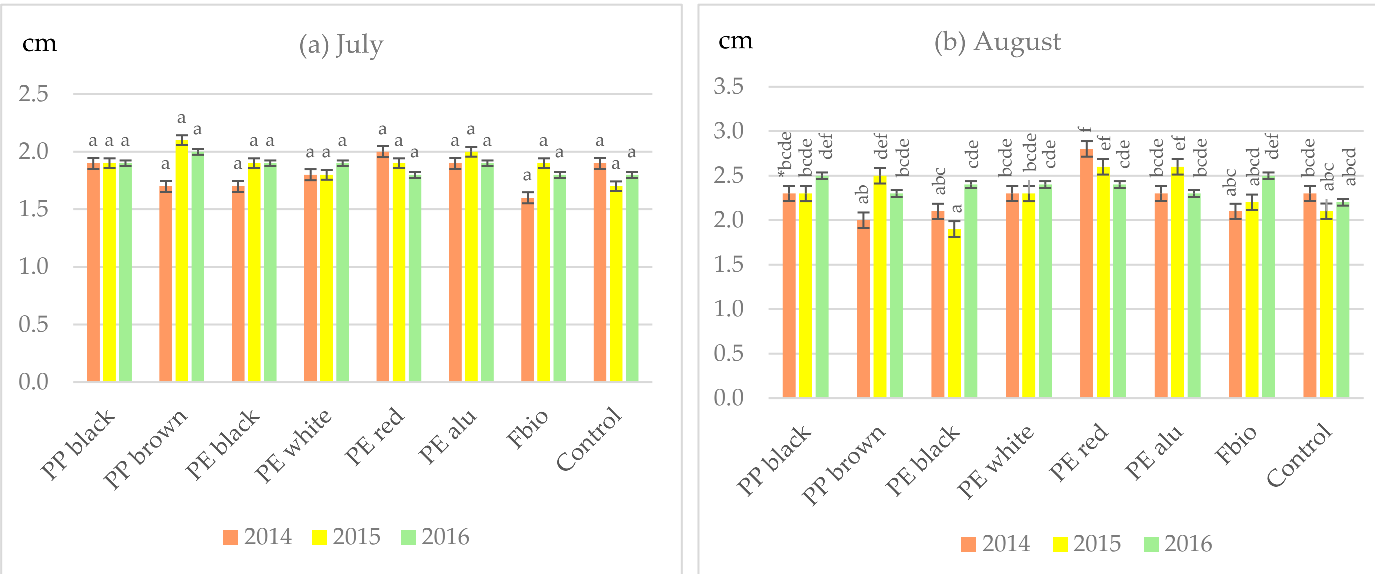

Figure 2. Tomato plant stem diameter depending on the type of mulch in 2014–2016 (cm). * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable.

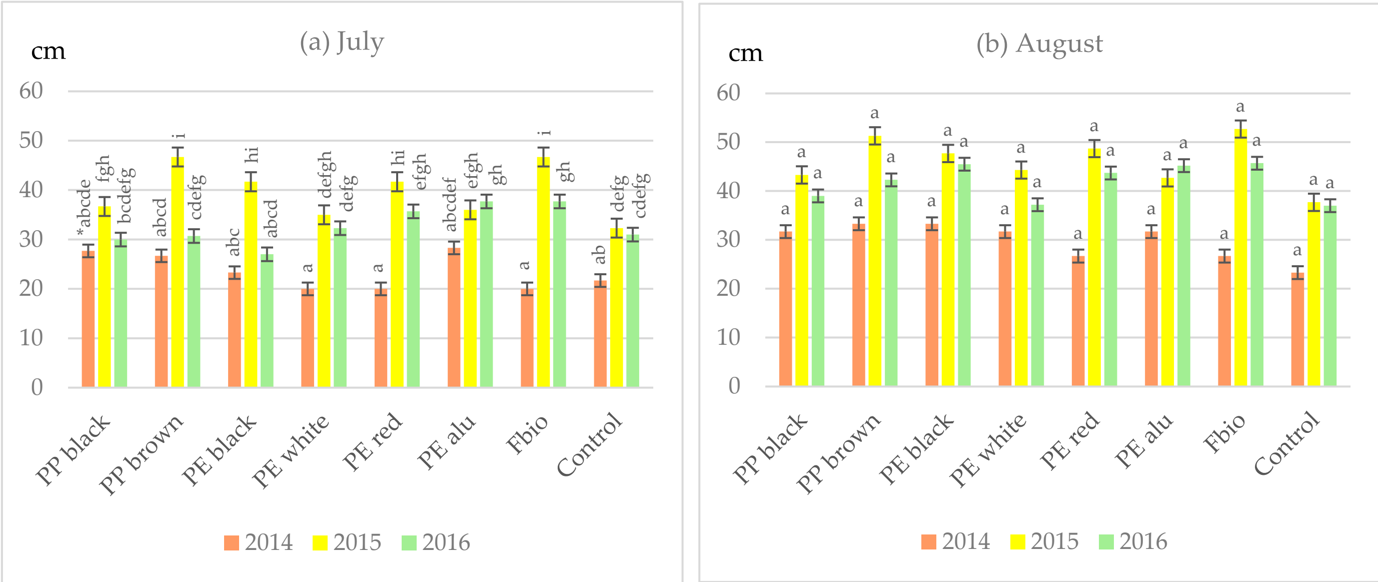

Figure 3. Tomato lateral spread depending on the type of mulch in 2014–2016 (cm). * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable.

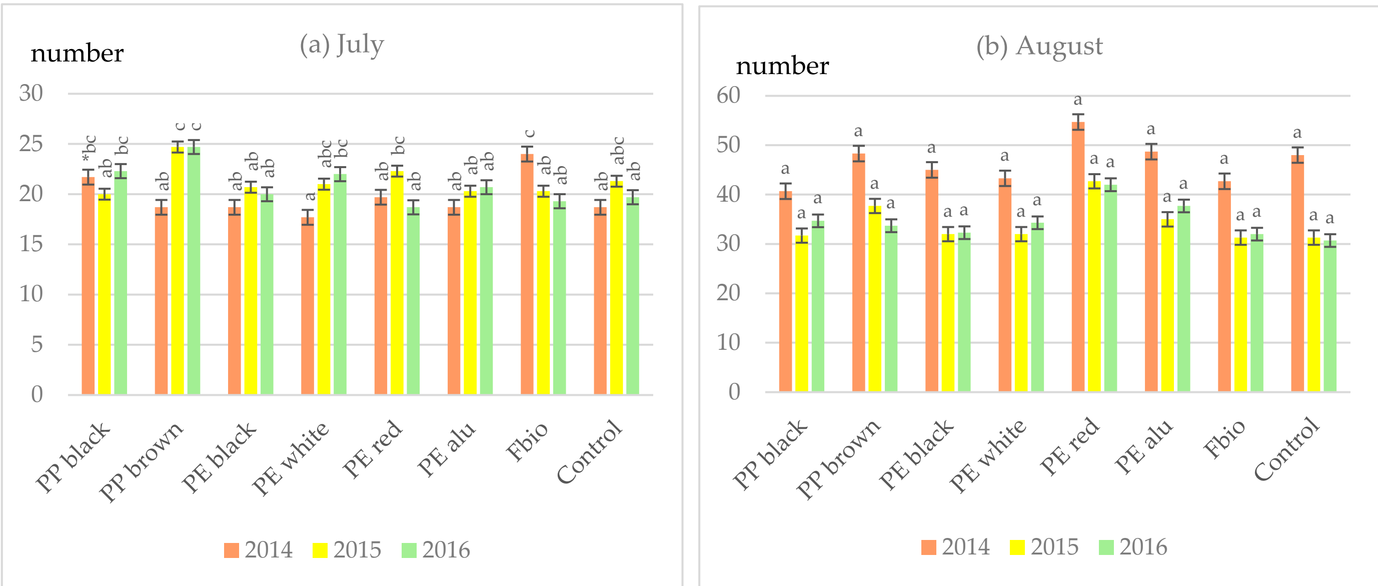

Figure 4. Tomato leaf number depending on the type of mulch in 2014–2016. * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable.

Table 1. Tomato plant morphology parameters average for years.

Parameters	2014		2015		2016	
	July	August	July	August	July	August
Plant height (cm)	112.0 *a	148.5 A	124.2 b	152.5 B	110.5 a	153.4 B
Plant stem diameter (cm)	1.8 a	2.3 A	1.9 a	2.3 A	1.9 a	2.4 A
Lateral spread (cm)	23.5 a	29.8 A	39.6 c	46.0 C	32.8 b	41.9 B
Number of leaves (szt.)	10.7	46.4 B	21.3	34.2 A	20.9	34.7 A

* The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Lower letters mark significance differences in July; capital letters mark significance differences in August.

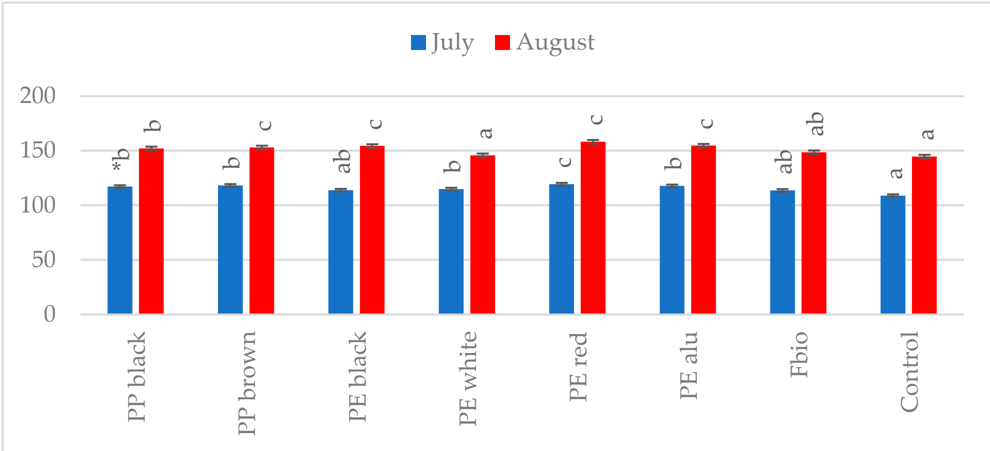

Figure 5. Tomato plant height in July and August depending on the type of mulch. Average for 2014–2016 (cm). * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Letters refer to type of mulch. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable.

In the present study, it was observed that field-grown tomato plants mulched with synthetic materials exhibited significantly greater height, stem diameter at the base, lateral spread, and leaf number compared to the control plot (Figure 6). Among the mulches applied, both black and red E films had a pronounced effect on tomato development [22].

Pinder et al. [22] reported that mulching with black PE film resulted in a significant increase in the growth of small-fruited tomato plants. Similarly, Islam [23] noted a positive impact of black PE film mulching on the vegetative development of tomatoes, with plants exhibiting increased height, more stems, and a higher fruit count, ultimately leading to significantly higher yields compared to plants grown without mulch. Onunva et al. [24] also observed enhanced plant height and stem and leaf numbers as well as improved flowering and fruiting in tomato plants grown with synthetic mulches. Furthermore, the beneficial effects of red PE film on plant growth were also confirmed by Agrawal et al. [25]. In July, plants grown with mulch were, on average, 7% taller than those in the control treatment. The stem diameter at the base ranged from 1.8 to 2.0 cm, while the lateral spread of the plants (28.3–34.8 cm) and the number of leaves (19.8–22.7) were not significantly influenced by the type of mulch used. It was observed that, during the second measurement period, mulched plants were, on average, 5.3% taller than those in the control group, with a 22.9% greater lateral spread and 5.4% more leaves (Figures 5 and 6). Plants mulched with red PE film exhibited the greatest height (158.3 cm), stem diameter (2.6 cm), and leaf number (46.4 leaves). Plants mulched with black PE and aluminum films showed similar heights, while those mulched with brown PP nonwoven fabric and aluminum film had comparable leaf numbers. All mulches applied resulted in an average 22.9% increase in lateral spread compared to the control. Tomatoes grown on white PE film mulch exhibited the lowest height. The use of Fbio mulch ensured a similar condition of the plants as in the other mulches. The exception was the height of the plants, which was among the smallest in both measurement terms, and the number of leaves in August.

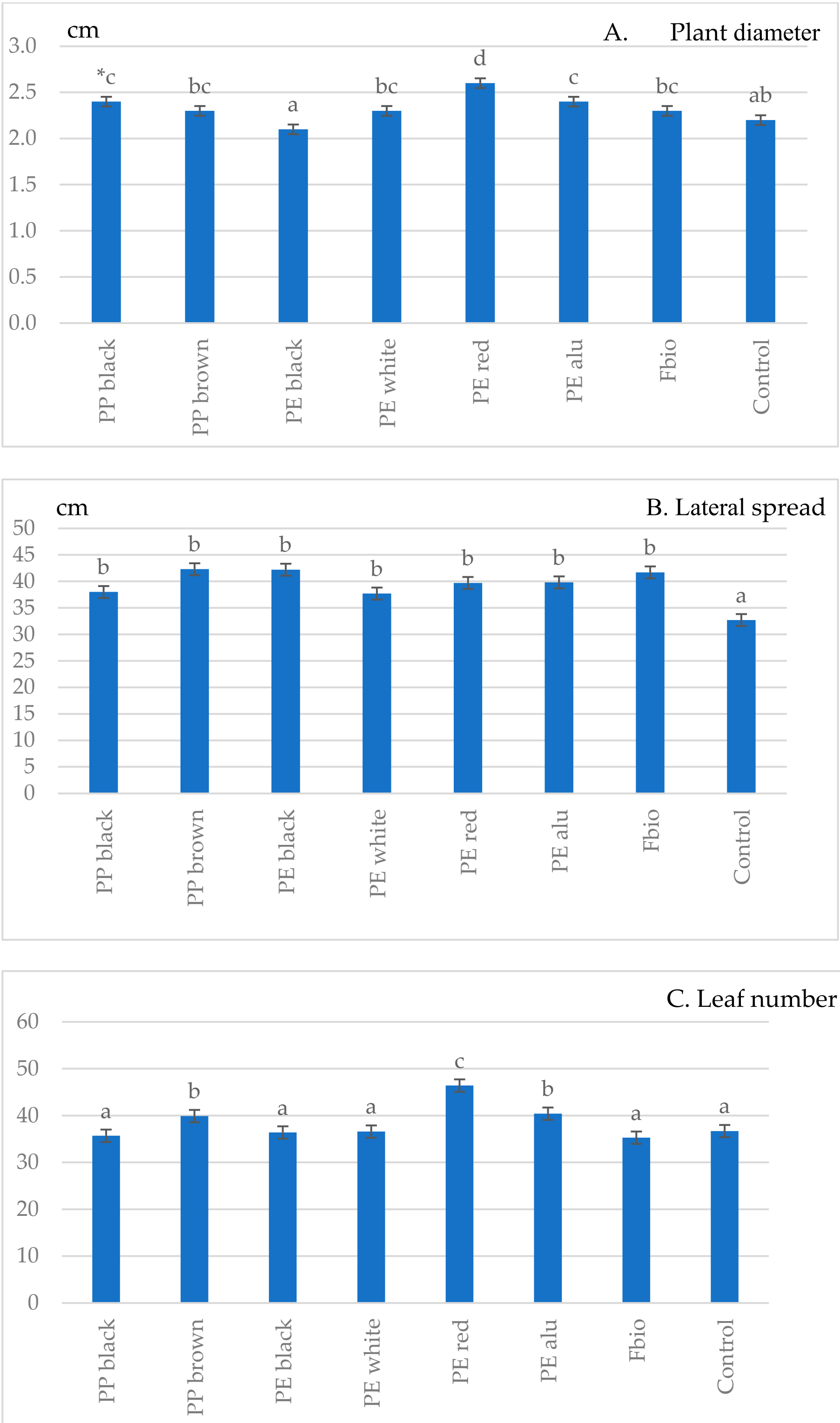

Figure 6. Tomato plant diameter, span, and leaf number in August depending on the type of mulch. Average for 2014–2016. * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05.

3.2. Yield Performance

The study results, subjected to statistical analysis, demonstrated that weather conditions and the type of synthetic mulch applied significantly influenced the yield of the Intrigo F1 tomato cultivar (Table 2). The lowest average total fruit yield was recorded in 2014 (8.04 t·ha^{-1}), attributable to adverse weather conditions. In 2016, the yield increased 2.3-fold, while in 2015, it was approximately three times higher than in 2014.

Table 2. Total, marketable, and early yield of Intrigo F1 tomato fruit depending on the type of mulch in 2014–2016 [t·ha^{-1}].

Type of Mulch	Total Yield				Marketable Yield				Early Yield			
	2014	2015	2016	Mean	2014	2015	2016	Mean	2014	2015	2016	Mean
PP black	11.36	26.96	19.30	19.71 **c	9.95	19.59	11.33	13.62 d	1.44	3.53	3.22	2.73 ab
PP brown	7.86	28.45	15.13	17.15 ab	6.38	20.65	8.93	11.99 c	1.16	3.85	2.32	2.44 a
PE black	4.35	27.28	17.82	16.48 ab	3.77	19.58	10.38	11.24 abc	0.79	4.03	3.85	2.89 b
PE white	8.23	25.31	19.08	17.54 ab	6.49	17.87	10.87	11.74 bc	1.71	4.56	4.08	3.45 cd
PE red	6.06	23.39	17.65	15.70 a	5.45	16.21	9.47	10.38 ab	2.00	4.28	3.43	3.24
PE alu	6.73	27.09	20.88	18.23 bc	5.58	18.20	12.33	11.97 c	1.83	4.41	5.02	3.75 d
Fbio	8.59	23.49	17.38	16.49 ab	6.72	17.34	9.12	11.06 abc	2.17	3.88	2.00	2.68 ab
Mean	**7.58**	**26.00**	**18.18**	**17.25**	**6.33**	**18.49**	**10.25**	**11.72**	**1.59**	**4.08**	**3.42**	**3.03**
Control	11.21	15.51	21.55	16.09 a	9.14	10.15	10.10	9.80 a	2.54	3.34	3.27	3.05 bc
Mean	**8.04 *A**	**24.69 C**	**18.60 B**	**17.10**	**6.67 A**	**17.45 C**	**10.29 B**	**11.48**	**1.70 A**	**3.99 B**	**3.40 B**	**3.03**

The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for $\alpha = 0.05$. * Capital letters refer to years, ** lower letters refer to type of mulch. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

Extensive research has indicated that soil mulching fosters vegetable yield improvement [13,26,27]. The effectiveness of this practice, however, may vary depending on the type of mulching material utilized [28]. Based on the averages across the experimental years, the highest total fruit yield was achieved in cultivation using black PP nonwoven fabric (19.17 t·ha^{-1}), with a comparable yield observed when aluminum foil mulch was employed. In other treatments, the yield ranged from 15.70 to 17.54 t·ha^{-1}. Over the course of the study, the highest total yield was recorded in 2015 with brown PP mulch (28.45 t·ha^{-1}), whereas the lowest yield was observed in 2014 with black PE film mulch (4.35 t·ha^{-1}). During the hot and dry conditions of 2015, mulching significantly enhanced the total yield, resulting in an average increase of 67.6% in mulched treatments compared to the control.

The marketable yield of Intrigo F1 tomato fruits accounted for an average of 67% of the total yield, with values ranging from 6.67 t·ha^{-1} in 2014 to 17.45 t·ha^{-1} in 2015. Statistical analysis revealed a significant positive effect of synthetic mulching materials on marketable yield; however, the magnitude of this effect varied across the study years. In 2015, a yield increase of 82.2% in marketable yield was observed in mulched treatments compared to the control. On average, across all experimental years, mulching resulted in a 19.6% increase in marketable yield relative to the control. Di Mola et al. [29] demonstrated that cultivating large-fruited tomatoes using black PE and biodegradable mulches produced a comparable yield increase of 25%. Similarly, Agrawal et al. [25] reported that black and red PE mulches increased tomato yields by 45.5% and 40.1%, respectively, compared to the control. Rajablariani et al. [30] observed marketable yield increases of 65% with black-and-aluminum mulch, 50% with black PE mulch, and 26% with red PE mulch. In the present study, the highest marketable yield (13.62 t·ha^{-1}) was recorded in treatments with black nonwoven fabric, representing a 39% increase compared to the control. Marketable yields from brown PP, black, white, biodegradable, and aluminum PE mulches averaged 11.60 t·ha^{-1}, which exceeded the control yield by 18.4%. Over the experimental period, the maximum marketable yield was observed in 2015 on brown nonwoven fabric, reaching 20.65 t·ha^{-1}. For tomato cultivation on Fbio, the marketable yield of Intrigo fruit constituted an average of 67.1% of the total yield. The total and marketable yield was lower by 16.4% and 18.8%, respectively, compared to the highest yield obtained from black PP.

The early yield of Intrigo F1 tomato fruits exhibited variability across the study years, ranging from 1.70 t·ha^{-1} in 2014 to an average of 3.70 t·ha^{-1} in subsequent years. Statistical analysis confirmed that the type of synthetic mulch employed had a significant effect on early yield. The highest early yield was obtained in treatments with aluminum foil mulch and white PE film mulch, averaging 3.60 t·ha^{-1}. By contrast, the lowest early yields were recorded in treatments with black and brown PP nonwoven fabric and biodegradable mulches, averaging 2.62 t·ha^{-1}. The most pronounced effect of mulching was observed in 2015, where it led to an average yield increase of 22% compared to the control (non-mulched) treatments. Over the study period, the maximum early yield was recorded in 2016 on aluminum foil mulch (5.02 t·ha^{-1}), with a comparable yield observed in 2015 on white PE film and aluminum foil mulches.

The highest number of fruits per cluster was recorded in 2015 (16.6 fruits), whereas the number was approximately 31.4% lower in 2014 and 2016. The largest mean number of fruits per cluster was observed in plants grown on black PP nonwoven fabric (15.1 fruits), with comparable values recorded for brown PP nonwoven fabric and black PE film mulches (Figure 7). These numbers exceeded those recorded in the control treatments by 24.8% and an average of 14.5%, respectively. On the Fbio mulch, the number of fruits per cluster was at the same level as in the control. Di Mola et al. [29] observed a 31.3% increase in the number of fruits on black PE and biodegradable mulches compared to non-mulched cultivation. The mean fruit mass per cluster ranged from 266.3 g in 2014 to 230 g in 2016. Statistical analysis revealed no significant effect of synthetic mulch type on the average fruit mass per cluster (Figure 8). However, slightly higher fruit masses were observed in plants cultivated on black PP nonwoven fabric (266.7 g).

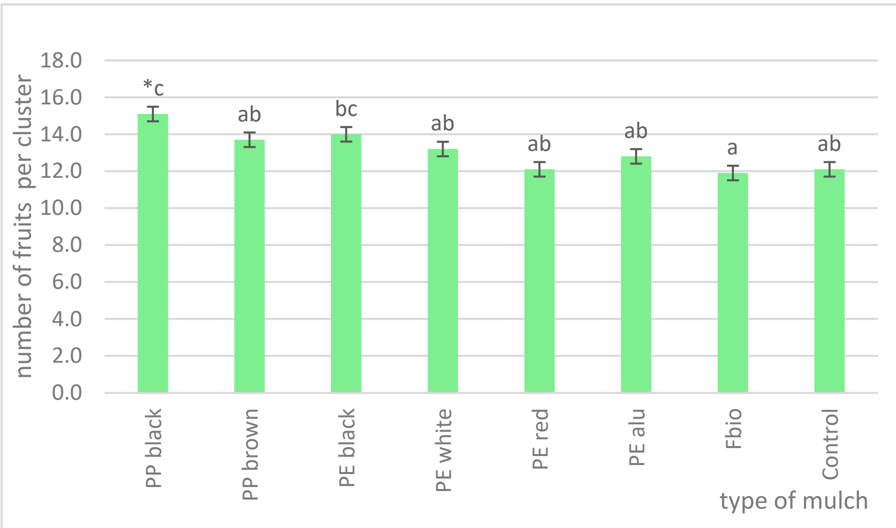

Figure 7. Number of fruits per cluster depending on the type of mulch. Average for 2014–2016. * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for α = 0.05. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

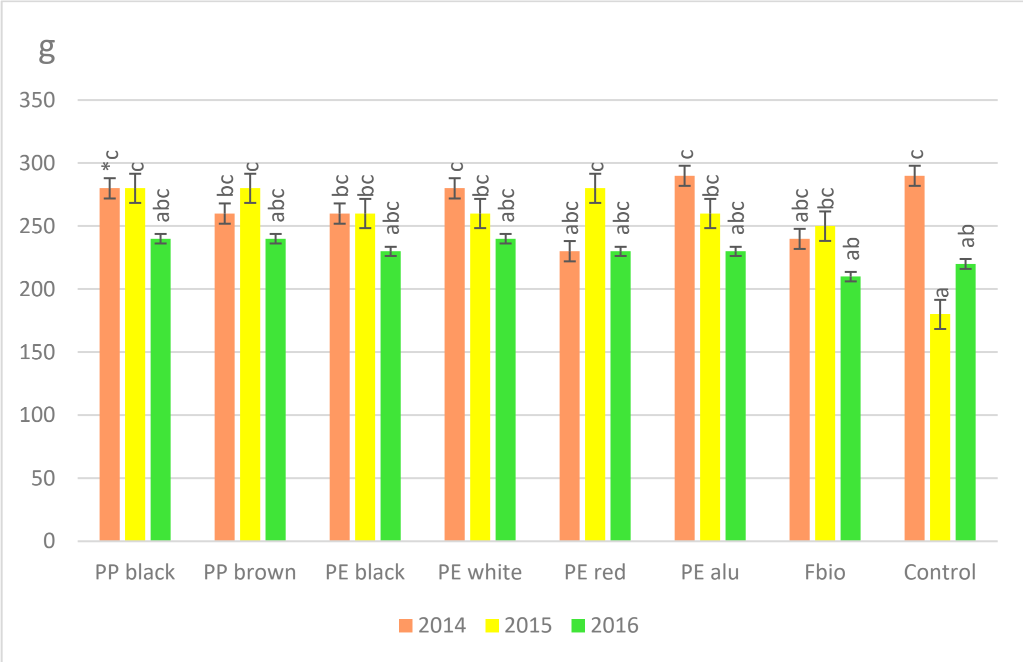

Figure 8. Fruit mass from one cluster depending on the type of mulch in 2014–2016 (g). * The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for $\alpha = 0.05$. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

3.3. Chemical Composition of Tomato Fruits

Tomatoes are among the most widely consumed vegetables worldwide due to their unique flavor and high nutritional profile. In addition to essential macro- and micronutrients, tomato fruits are rich in secondary metabolites, such as ascorbic acid, sucrose, hexoses, citrates, and malates. They also accumulate bioactive compounds beneficial to human health, including carotenoids, phenylpropanoids, and terpenoids [31–34]. Raffo et al. [35] reported that cherry tomatoes typically contain higher levels of antioxidants compared to standard-sized varieties. They demonstrated that fully ripe cherry tomatoes exhibit the highest concentrations of carotenoids and antioxidant activity, while ascorbic acid levels remain relatively stable throughout the ripening process.

The chemical composition of vegetables is primarily determined by genetic factors but can be significantly influenced by external variables, such as climatic conditions and agronomic practices, during the plant's growth cycle [35,36]. In this study, the application of synthetic mulches significantly affected the chemical composition of the Intrigo F1 tomato cultivar. The impact of mulching varied by the type of material and its color (Tables 3 and 4). On average, higher concentrations of organic compounds, phosphorus (P), and potassium (K), as well as elevated DPPH radical scavenging activity, were observed in fruits grown with PE film mulches compared to PP nonwoven fabric and control treatments. Tomatoes grown on biodegradable mulches demonstrated lower levels of dry matter, total sugars, phosphorus, vitamin C, and carotenoids while accumulating higher concentrations of polyphenols, lycopene, and potassium compared to fruits cultivated on PE film mulches.

Table 3. The content of dry matter, total sugars, and macronutrients in Intrigo F1 tomato fruit depending on the type of mulch (%). Average for 2014–2016.

Type of Mulch	Dry Matter	Total Sugars	P	K	Mg	Ca
			%			
PP black	9.02 *cd	4.11 a	0.25 a	3.43 cd	0.16 a	0.26
PP brown	8.71 ab	4.32 ab	0.31 bc	3.00 a	0.22 bc	0.27
PE black	8.48 a	4.09 a	0.35 d	3.48 d	0.20 abc	0.25
PE white	9.22 de	5.41 d	0.27 a	3.31 bc	0.22 bc	0.28
PE red	9.38 e	4.85 c	0.32 cd	3.31 bc	0.19 ab	0.28
PE alu	8.51 a	4.50 bc	0.32 cd	3.10 a	0.24 c	0.26
Fbio	8.81 bc	4.06 a	0.28 ab	3.82 e	0.20 abc	0.23
Control	8.57 a	4.71 c	0.33 c	3.25 b	0.20 abc	0.29

* The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for $\alpha = 0.05$. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

Table 4. The content of vitamin C, carotenoids, polyphenols, lycopene, and N-NO3$^-$ and the value of DPPH in Intrigo F1 fruits depending on the type of mulch. Average for 2014–2016.

Type of Mulch	Vitamin C [mg·100 g^{-1} f.m.]	Polyphenols	Carotenoids [µg·100 g^{-1} f.m.]	Lycopene [mg·kg^{-1} f.m.]	DPPH [%]	N-NO$_3^-$ [mg·kg^{-1} f.m.]
PP black	36.81 *a	16.19 a	38.22 c	19.10 abc	58.73 b	120.33 d
PP brown	39.87 cd	24.32 c	37.27 c	16.36 a	68.96 d	118.18 cd
PE black	41.79 e	19.57 b	41.44 d	17.67 ab	56.42 a	102.35 ab
PE white	41.88 e	21.11 b	39.26 cd	18.65 abc	71.52 e	98.86 a
PE red	39.74 c	26.97 d	32.27 ab	20.91 cd	65.22 c	118.54 cd
PE alu	40.59 d	36.46 f	30.10 a	20.33 bcd	70.45 de	106.69 abc
Fbio	37.84 b	30.69 e	31.11 ab	22.31 d	59.61 b	107.57 abcd
Control	36.57 a	27.41 d	33.64 b	20.35 bcd	56.18 a	111.55 abcd

* The same letters mark values belonging to the same homogeneous groups, determined on the basis of statistical analysis for $\alpha = 0.05$. Type of mulch: PP nonwoven: black and brown; PE film: black, white, red; PE alu—aluminum film; Fbio—biodegradable film.

Fruits harvested from red and white PE mulch exhibited the highest dry matter content, averaging 9.30%, with comparable levels observed in fruits grown on black PP nonwoven fabric (9.02%). Significantly lower dry matter levels were detected in fruits from treatments using black PE mulch, aluminum foil mulch (PE alu), and control plots. These findings align with those of Hallmann and Rembiałkowska [37], who reported an average dry matter content of 7.36% in the small-fruited tomato cultivar Koralik. Sugars, the primary component of tomato pulp extract, play a critical role in determining fruit flavor and palatability, with higher sugar concentrations enhancing fruit quality. In the current study, fruits grown on white PE mulch demonstrated the highest total sugar content (5.41%), followed by those grown on red PE film (4.85%) and aluminum foil mulch (4.50%). These results are consistent with findings by Shahzad et al. [38], who confirmed the significant contribution of sugars to the sweet taste and nutritional value of small-fruited tomatoes (*Solanum lycopersicum* var. *cerasiforme*). Hallmann and Rembiałkowska [37] reported a total sugar content of 2.62% in Koralik small-fruited tomatoes. By contrast, Kowalczyk et al. [39] observed a higher sugar concentration in the greenhouse-grown small-fruited cultivar Dasher F1, which exhibited 3.66 g of total sugar per 100 g of fresh weight, surpassing medium-fruited varieties. Similarly, Gharezi et al. [40], in their analysis of six small-fruited tomato cultivars, documented sugar concentrations ranging from 3.14 to 4.81 mg per 100 g.

Key bioactive compounds in tomatoes include carotenoids, with lycopene being the primary carotenoid responsible for the red color of tomatoes, along with β-carotene. According to Li et al. [33], β-carotene is considered the most efficient source of provitamin A among carotenoids. The present study revealed a significant influence of the type of synthetic mulch on the carotenoid content in Intrigo F1 tomato fruits. The highest carotenoid concentrations were recorded in fruits from plants grown under black PE mulch (41.44 µg·100 g^{-1} fresh weight), which was approximately 23% higher compared to the control. Slightly lower levels were observed in fruits from plants mulched with white PE (5.3% lower) and black and brown PP (on average 9.0% lower). The lowest carotenoid content (30.10 μg·100 g^{-1} fresh weight) was found in fruits from plants grown with aluminum foil mulch (PE alu). Di Mola et al. [29] reported that, under Southern European conditions, the average increase in carotenoid content in fruits of traditional tomato varieties grown on black mulches (PE and biodegradable) was 57%. Dobromilska et al. [41] observed carotenoid concentrations in the small-fruited Conchita F1 cultivar ranging from 0.43 to 0.62 mg·g^{-1} fresh weight.

Lycopene exhibits strong antioxidant and anticancer properties. According to Kuti and Konuru [32], both the cultivar and the growing environment have a significant influence on the lycopene content in tomatoes. The authors observed that compared to other varietal groups, cocktail tomato fruits accumulate higher levels of lycopene. In field cultivation, the lycopene content in these fruits was estimated to be an average of 91.9 mg kg^{-1} fresh weight (f.w.), while in greenhouse cultivation, it averaged 56.1 mg kg^{-1} f.w. Bilalis et al. [42] reported lycopene contents of 88.5 and 80.5 mg kg^{-1} f.w. for tomatoes fertilized organically and with inorganic fertilizers, respectively, while Jędrszczyk and Ambroszczyk [43] reported values of 4.29–6.82 mg 100 g^{-1} f.w. in their studies. The present research found a significant effect of the type of mulching material on the lycopene content in cocktail tomato fruits. Biodegradable mulch resulted in the highest lycopene concentration (22.31 mg kg^{-1} fresh weight). Fruits from plants mulched with red PE film, PE alu, and the control treatment exhibited similar lycopene levels, ranging from 20.91 to 20.33 mg kg^{-1} fresh weight.

Tomato fruits contain a variety of phenolic compounds, such as flavonoids, caffeoylquinic acids, and other hydroxycinnamates. Cruz-Carrion et al. [34] identified 57 different polyphenolic compounds in tomato fruits. Their concentration varied depending on the cultivation site. In the present experiment, the highest polyphenol content was recorded in tomatoes grown under aluminum foil (36.46 mg·100 g^{-1} fresh weight). Significantly lower levels, 15.8% less, were found in fruits from biodegradable film, and 25.4% less on average in fruits from red film and the control group. Cruz-Carrion et al. [34] reported an average total polyphenol content of 3554 μg·g^{-1} fresh weight in tomato fruits. Morra et al. [44] found that fruits from plants mulched with biodegradable black Mater-Bi foils had more polyphenols and lycopene and higher antioxidant activity compared to LDPE and unmulched soil.

The vitamin C content in Intrigo F1 tomato fruits ranged from 36.57 to 41.88 mg·100 g^{-1} fresh weight. It was demonstrated that mulching (except for black PP) significantly increased the content of this component compared to the control. The greatest increase, averaging 14.4%, was observed in the treatments with white and black PE film. In crops grown under red foil, aluminum foil, and brown PP fabric, the increase averaged 9.6%, and it averaged 3.5% on biodegradable film. Gharezi et al. [40] reported vitamin C levels in small-fruited tomato varieties ranging from 23.6 to 28.1 mg·100 g^{-1}. In research by Jędrszczyk and Ambroszczyk [43], the amount of this component in tomato fruits grown in the field ranged from 10.77 to 28.9 mg 100 g^{-1} f.w.

Minoggio et al. [45] highlighted the high biological value of tomato fruits, particularly due to the significant antioxidant activity of the polyphenols they contain. Through studies on various tomato lines and cultivars examining the relationship between polyphenol, lycopene, and beta-carotene content and total antioxidant activity (TAA), it has been established that nearly all lines with low carotenoid content produce high levels of polyphenols and consequently exhibit the strongest antioxidant potential. In our own research, the highest DPPH index (71.52%) was observed in tomatoes grown on white film, with comparable levels found in fruits grown on aluminum film (70.45%) and brown PP film (68.96%). The lowest antioxidant activity was recorded in tomatoes grown on black PE film and in the control group (56.30% DPPH).

The lowest nitrate nitrogen content in fruits (98.86 mg·kg^{-1} fresh weight) was observed in fruits grown under white film mulch. At the same level of significance, nitrate levels were similar in fruits from treatments with black PE film, aluminum film, and biodegradable film and the control. The highest nitrate content was recorded in fruits from the black fabric mulch treatment (120.33 mg·kg^{-1} fresh weight). Dobromilska et al. [41] reported nitrate contents in cocktail tomato fruits grown in a plastic tunnel ranging from 200 to 245 mg·kg^{-1} fresh weight.

The macronutrient content in tomato fruits varied depending on the type of mulch used. The phosphorus content ranged from an average of 0.27% (black PP, white PE, biodegradable fabric) to 0.33% (red PE, aluminum fabric, black PE) in fresh weight. Potassium content ranged from 3.05% (brown PP, aluminum fabric) to 3.46% (black PE, black PP) and 3.82% (biodegradable fabric). Magnesium content ranged from 0.16% (black PP) to 0.24% (aluminum fabric). Dobromilska et al. [41] reported phosphorus contents in Conchita F1 fruits grown in a plastic tunnel of 4.86–6.40 g·kg^{-1} fresh weight, potassium contents of 24.90–32.7 g·kg^{-1}, calcium contents of 1.55–2.10 g·kg^{-1}, and magnesium contents of 1.00–1.40 g·kg^{-1}.

4. Conclusions

The growth of plants, as well as the quantity and quality of the yield of the small-fruited tomato variety Intrigo F1, were significantly influenced by the weather conditions during the growing season. According to the observations, it can be concluded that the primary yield-determining factor for tomatoes is the temperature regime at transplanting. The second crucial factor is water availability. During the first part of the growing season, adequate water supply promotes vegetative development, flower formation, and fruit set.

Plants grown with synthetic mulches exhibited greater height, stem diameter at the base, lateral spread, and leaf number compared to those grown without mulch. A somewhat weaker effect on tomato plants was observed when using biodegradable film. Tomatoes grown on biodegradable film yielded slightly more than those in the control. A broader use of this mulch is encouraged due to the fact that it has a similar effect on the soil environment and plant surroundings as other mulches, without the issue of removal and disposal from the field. Soil mulching improved tomato growth conditions and fruit quality due to higher soil temperatures and consistent moisture, especially compared to bare ground.

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