

## Article

# Effects of Grafting and Fertilization Treatments on the Functional and Nutritional Quality of Eggplant Cultivars

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## Abstract

The nutritional and functional quality of eggplants is heavily influenced by biological and technological factors. This study evaluated the effects of cultivar, rootstock, and fertilizers on the nutritional and functional quality of eggplant (*Solanum melongena* L.). Two commercial hybrids (Mirval and Black Pearl) were assessed with respect to two rootstocks (*Solanum sylvatica* and Rezistar F1) and three fertilization regimes: biological (Micoseed<sup>®</sup>), organic (Orgevit<sup>®</sup>), and chemical (Nutrispore<sup>®</sup>). These were compared with ungrafted and unfertilized cultivars. Fruit samples were analyzed for total polyphenol content (TPC), antioxidant capacity (ABTS and DPPH assays), chlorophyll a and b, lycopene, and tannin concentrations. Mirval exhibited significantly higher levels of TPC, antioxidant activity, photosynthetic pigments, and lycopene than Black Pearl. Ungrafted plants and those grafted onto *S. sylvatica* showed superior fruit quality, particularly when combined with organic or chemical fertilization. The highest concentrations of polyphenols (3.61 mg·100 g<sup>−1</sup> DW), lycopene (3.18 mg·100 g<sup>−1</sup> DW), and total chlorophylls were recorded for Mirval fruits from ungrafted or *S. sylvatica*-grafted plants under organic or chemical fertilization. These findings indicate that optimizing cultivar–rootstock combinations and fertilization management can significantly enhance the functional quality of eggplant fruits. The findings also support the use of organic fertilization as a sustainable strategy in protected vegetable production systems.

**Keywords:** functional quality; bioactive compounds; antioxidant activity; polyphenol content; lycopene; cultivation method



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## 1. Introduction

Eggplant (*Solanum melongena* L.) is cultivated predominantly in subtropical regions, which account for approximately 94% of global production. Due to its wide popularity and economic relevance, it is often referred to as a vegetable with a higher potential. According to the Food and Agriculture Organization of the United Nations (FAO) [1], China and

India are the world's leading producers, with annual outputs of approximately 38 and 13 million tons, respectively. In Europe, production is mainly concentrated in Turkey (781,000 t), Italy (307,400 t), Spain (276,300 t), and Romania (64,600 t per year) [2]. Globally, eggplant ranks sixth among vegetable crops in total production, after tomato, watermelon, onion, cucumber, and cabbage, with 56.6 million tons produced in 2024 (WPR, 2026) [3]. Approximately 65–70% of global production is processed, while consumption also includes cooked, stuffed, marinated, and fried products [4].

Eggplant is valued for its ecological adaptability, consumer acceptance, and diverse cultivation [5]. Its fruits contain carbohydrates, sugars, proteins, and vitamin C, as well as bioactive compounds, including polyphenols, lycopene, tannins, and other antioxidant molecules, which collectively contribute to both its nutritional and functional properties [6,7]. For example, the lycopene and other carotenoids present in eggplant fruits are associated with reduced risks of cancer and cardiovascular diseases, largely due to their antioxidant properties [8]. Tannins, also known as proanthocyanidins, represent another important group of bioactive compounds, exhibiting antioxidant, anti-inflammatory, anticancer, anti-atherosclerotic, and cardioprotective effects [9].

Over the past three decades, numerous cultivars have been introduced into European and Romanian markets; however, many show limited adaptation to changing climatic conditions and shifting consumer preferences. Recent studies indicate that cultivar selection, fertilization strategy, and irrigation regime are key factors affecting both yield and quality in organic and conventional systems [5].

The grafting of eggplant (*S. melongena* L.) represents an effective strategy to enhance fruit quality by improving nutrient uptake efficiency, stress tolerance, and secondary metabolite accumulation. Rootstock–scion interactions can modulate antioxidant activity, phenolic content, and pigment concentration, thereby influencing the functional and nutritional value of the fruits. Several studies have demonstrated that appropriate rootstock selection enhances biochemical-quality traits and antioxidant responses in eggplant under both optimal and stress conditions [10–12].

Plant nutrition plays a central role in eggplant growth, productivity, and fruit quality. Fertilization strongly influences soil properties, plant physiological processes, photosynthetic efficiency, and the accumulation of bioactive compounds, such as chlorophylls and flavonoids, in fruits [13]. Organic fertilizers and biological amendments improve soil structure and microbial activity, while chemical fertilizers provide rapid nutrient availability and high yields [14–16]. Therefore, the selection of appropriate fertilization strategies is critical for optimizing both productivity and nutritional quality. Increasingly, research efforts have focused on identifying cultivation practices that enhance fruit functional properties while maintaining sustainable production systems [17,18].

Modern agricultural systems often prioritize yield maximization, sometimes at the expense of environmental sustainability and long-term soil fertility, to the detriment of fruit quality [19]. Increasing consumer demand for healthier foods and stricter regulations on environmental protection have accelerated the transition toward sustainable agricultural practices, including organic farming [20]. As a result, the global area under organic cultivation and the organic food market have expanded steadily, with a further increase in consumer demand observed during the COVID-19 pandemic [21]. Organic production systems are considered beneficial due to reduced chemical inputs and improved soil health, contributing to enhanced ecosystem resilience and potentially to the improved nutritional quality of produce [22].

Previous studies have demonstrated that suitable combinations of cultivar selection and fertilization management can significantly enhance the accumulation of bioactive compounds under varying climatic conditions [23,24]. However, comparative studies

evaluating the combined effects of fertilization regimes and cultivation systems on the nutritional quality of eggplant, under protected conditions, remain limited.

Therefore, this research aimed to assess the effects of two eggplant varieties grafted onto two different rootstocks, under three fertilization regimes. Comparisons were made among controls, individual varieties, and various interactions with respects to the nutritional and functional quality fruits. The findings from this study could significantly enhance the composition of eggplants fruits, particularly in terms of total polyphenol content, antioxidant activity, chlorophyll a and b, lycopene, and tannins.

## 2. Materials and Methods

### 2.1. Experimental Site and Design

The experiment was carried out under plastic tunnel at the “V. Adamachi” Farm of the Iași University of Life Sciences, Romania (47°19'25" N, 27°54'99" E; 150 m a.s.l.) during the 2021 and 2022 growing seasons, following the same experimental design and management practices. The experiment included three experimental factors: cultivar, rootstock, and fertilizer. Two eggplant hybrids, Mirval F1 and Black Pearl F1, were used as scions for two rootstocks (*Solanum sylvatica* and Rezistar F1), which were then compared with controls (ungrafted plants). The fertilization treatments consisted of three regimes: biological (Micoseed®, Agrofert, Ltd., Bucharest, Romania), organic (Orgevit®, GVAMarcom Ltd., Galati, Romania), and chemical (Nutrispore®, Agrofert, Ltd., Bucharest, Romania), which were compared with the unfertilized controls. The complete list of experimental variants is provided in Supplementary Table S1. The experiment was organized in a split-split-plot design with 24 experimental variants and three replicates ( $n = 3$ ). The plants were grafted using the cleft grafting method, at a 45-degree angle, when the stem in the grafting area was at least 6 mm thick (35-day-old scion and 40-day-old rootstock).

### 2.2. Plant Production and Crop Management

Seedlings were produced in multicellular trays under organic-compliant conditions and transplanted into the plastic tunnel at 55 days after sowing, in mid-April, at a density of 2.5 plants·m<sup>-2</sup>. During the experiment, the temperature in the greenhouses was not lower than 16–18 °C or higher than 34–36 °C.

Standard care practices were applied throughout the growing period, including plant-training, pruning, and integrated pest and disease management, in accordance with recommended vegetable practices [1,5]. The cultivation cycle ended on 31 October, with a period of approximately 26 weeks.

### 2.3. Fertilization Treatments

The experimental field's soil was identified as silty-clay chernozem, characterized by a pH of 7.20, electrical conductivity (EC) of 482  $\mu\text{S}\cdot\text{cm}^{-1}$ , calcium carbonate ( $\text{CaCO}_3$ ) content of 0.42%, organic matter content of 2.83%, carbon to nitrogen (C/N) ratio of 5.87, total nitrogen of 2.8 g·kg<sup>-1</sup>, and available phosphorus of 34 mg·kg<sup>-1</sup>. Soil analyses were performed at the Research Institute for Agriculture and Environment, Iași University of Life Sciences, Romania. Irrigation was applied daily using an automated irrigation system to avoid a water deficit and maintain adequate soil moisture throughout the growing season (approximately 60–70% of the soil's field capacity (FC)). Fertilizer application rates followed the manufacturers' recommendations. To ensure comparable nutrient inputs between chemical and organic fertilization, application rates were adjusted, considering that approximately 70% of the nutrients supplied by the organic fertilizer become plant-available during the first year after application.

Chemical fertilization (Ch) involved applying Nutrispore® NPK 20–20–20 (Agrofert, Ltd., Bucharest, Romania) at a rate of 200 kg ha<sup>−1</sup> prior to transplanting, followed by two applications of Nutrispore® NPK 9–18–27 + 2 MgO at a rate of 300 kg ha<sup>−1</sup> each during the growing season.

Organic fertilization (O) consisted of commercial chicken manure (Orgevit®, GVAMarcom Ltd., Galati, Romania), containing 65% organic matter, 4% total N, 2.5% P<sub>2</sub>O<sub>5</sub>, 2.3% K<sub>2</sub>O, 9.3% CaO, and 1.1% MgO, applied at a total rate of 2000 kg ha<sup>−1</sup>, with 1250 kg ha<sup>−1</sup> incorporated into the soil before transplanting and the remaining 750 kg ha<sup>−1</sup> applied 30 days after planting.

Biological fertilization (B) was applied using Micoseed® (Agrofert, Ltd., Bucharest, Romania) at 30 kg ha<sup>−1</sup>, split into two equal applications before transplanting and 30 days after planting, combined with 5 L ha<sup>−1</sup> Nutryaction® (Agrofert, Ltd., Bucharest, Romania), following the manufacturer's recommendations. The biological formulation contains arbuscular mycorrhizal fungi (*Claroideoglomus etunicatum*, *Funneliformis mosseae*, *Glomus aggregatum*, *Rhizophagus intraradices*), along with beneficial microorganisms from the genera *Trichoderma*, *Streptomyces*, *Bacillus*, and *Pseudomonas*.

#### 2.4. Sample Collection and Preparation

Five fruits from each replicate of every experimental version were harvested when they reached commercial maturity. Fruits were cut into approximately 1 cm pieces, homogenized, and freeze-dried using an ECO EVO freeze dryer (Tred Technology S.R.L., Ripalimosani, Italy). The dried samples were ground into powder and stored at −80 °C until chemical analysis. The biochemical composition was conducted at Iași University of Life Sciences (Horticulture Research Center) and Andalusian Institute of Agricultural and Fisheries Research and Training (IFAPA), Córdoba, Spain.

#### 2.5. Hydrophilic Extraction

Hydrophilic compounds were extracted using deionized water–methanol (20:80, v/v) containing 1% formic acid. Lyophilized samples (0.2 g) were extracted with 1 mL solvent, sonicated for 10 min, and centrifuged at 15,000 rpm for 15 min. The supernatant was collected and the residue was re-extracted under identical conditions. Combined extracts were stored at −80 °C until the analysis of antioxidant activity, total polyphenols, and condensed tannins.

#### 2.6. Determination of Total Polyphenol Content

Total polyphenol content (TPC) was determined using the Folin–Ciocalteu method, as described by Slinkard and Singleton [25]. Briefly, 10 µL of extract was mixed with 175 µL distilled water and 12 µL Folin–Ciocalteu reagent. After 3 min, 30 µL of 20% sodium carbonate solution was added. Samples were incubated for 1 h; absorbance was measured at 765 nm. Results were expressed as mg gallic acid equivalents per 100 g dry weight (mg GAE·100 g<sup>−1</sup> DW).

#### 2.7. Antioxidant Activity

Antioxidant capacity was evaluated using ABTS and DPPH assays with a Synergy HTX multimode microplate reader (Biotek Instruments, Winooski, VT, USA), following the method described in [26]. Results were expressed as mmol Trolox equivalents per 100 g dry weight (mmol TE·100 g<sup>−1</sup> DW).

#### 2.8. Determination of Condensed Tannins

Condensed tannins were quantified using the vanillin–HCl method described by Deepa et al. [27], with minor modifications. Hydrophilic extracts were mixed with vanillin–

methanol solution (4% *w/v*) and concentrated hydrochloric acid and incubated for 20 min in the dark at room temperature. Absorbance was measured at 500 nm; results were expressed as mg catechin equivalents per 100 g dry weight.

### 2.9. Pigment Extraction and Analysis

Lipophilic pigments were extracted following the method described by Nagata and Yamashida [28]. Lyophilized samples (0.2 g) were extracted with 1 mL hexane–acetone (4:6, *v/v*) in the dark, centrifuged at 15,000 rpm for 15 min, and re-extracted. Absorbance was measured at 453, 505, 645, and 663 nm using a Synergy HTX microplate reader. Concentrations of chlorophyll a, chlorophyll b,  $\beta$ -carotene, and lycopene were calculated using published equations [29,30].

### 2.10. Statistical Analysis

The effects of cultivar, grafting, and fertilization on eggplant fruit-quality traits were analyzed using both three-way and one-way analysis of variance (ANOVA). The three-way ANOVA was applied to evaluate the interaction effects among cultivar, grafting, and fertilization, while one-way ANOVA followed by Tukey's post hoc test at a significance level of  $p \leq 0.05$  was used to assess differences among treatment combinations within each factor. Statistical analyses were conducted using SPSS version 26 and Statistix v.9.0 software. Additionally, principal component analysis (PCA) was conducted in Origin Pro Lab 2026 free trial to explore patterns and relationships among fruit-quality parameters and treatment combinations.

## 3. Results

The three-way analysis of variance (ANOVA) performed on the complete data set (Supplementary Table S2) revealed that the main effects of cultivar, grafting, and fertilization, as well as the interactions between pairs of factors and the three-factor interaction, significantly influenced the quality of eggplant fruit. For most evaluated effects, *p*-values were below the established significance threshold ( $p \leq 0.05$ ). Exceptions were observed for the main effect of fertilization on total polyphenols ( $p = 0.635$ ) and for the main effect of cultivar on ABTS ( $p = 0.150$ ) and tannin content ( $p = 0.063$ ), which were not statistically significant. Therefore, the interpretation of the results was carried out taking into account the individual and combined effects of the three factors.

### 3.1. Effects of Cultivar on Eggplant Fruit Quality

The evaluation of cultivar influence indicated that most quality parameters showed significant varietal differences between the two hybrids (Table 1). Overall, Mirval F1 showed higher values than Black Pearl F1 for total polyphenol content (TPC), chlorophyll a, chlorophyll b, lycopene, and tannins ( $p \leq 0.05$ ). Mirval accumulated 38% more TPC than Black Pearl (2.969 vs. 2.145 mg GAE·100 g<sup>−1</sup> DW). Similarly, Mirval exhibited higher pigment concentrations, including chlorophyll a (3.440 vs. 2.189 mg·100 g<sup>−1</sup> DW), chlorophyll b (4.739 vs. 2.821 mg·100 g<sup>−1</sup> DW), and lycopene (1.582 vs. 0.934 mg·100 g<sup>−1</sup> DW). In contrast, ABTS and DPPH radical scavenging activities and tannin content did not differ among cultivars ( $p \geq 0.05$ ). These results indicate that Mirval F1 exhibits a stronger antioxidant and pigment profile, suggesting greater potential to improve nutritional quality under protected cultivation.

**Table 1.** Biochemical-quality parameters of eggplant fruits across cultivars.

| Cultivar | TPC<br>(mg GAE·100<br>g <sup>-1</sup> DW) | ABTS<br>(mmol TE·100<br>g <sup>-1</sup> DW) | DPPH<br>(mmol TE·100<br>g <sup>-1</sup> DW) | Chl. a<br>(mg·100 g <sup>-1</sup><br>DW) | Chl. b<br>(mg·100 g <sup>-1</sup><br>DW) | Lycopene<br>(mg·100 g <sup>-1</sup><br>DW) | Tannins<br>(mg CE·100<br>g <sup>-1</sup> DW) |
|----------|-------------------------------------------|---------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------------|--------------------------------------------|----------------------------------------------|
| MF1      | 2.969 ± 0.008 a                           | 0.998 ± 0.004                               | 1.234 ± 0.003 a                             | 3.440 ± 0.068 a                          | 4.739 ± 0.178 a                          | 1.582 ± 0.046 a                            | 0.105 ± 0.01 a                               |
| BPF1     | 2.145 ± 0.045 b                           | 0.978 ± 0.017                               | 1.196 ± 0.001 b                             | 2.189 ± 0.019 b                          | 2.821 ± 0.017 b                          | 0.934 ± 0.008 b                            | 0.101 ± 0.01 b                               |
| Sign.    | *                                         | ns                                          | *                                           | *                                        | *                                        | *                                          | *                                            |

MF1—Mirval F1; BPF1—Black Pearl F1. The values are presented as mean ± standard error of individual replicates. Within each column, ns—no statistically significant difference, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

### 3.2. Effect of Grafting on Fruit Quality

Significant effects of grafting were observed for most measured parameters, with the exception of ABTS antioxidant activity (Table 2). In general, ungrafted plants produced fruits with the highest pigment concentrations, whereas Rezistar F1 resulted in the lowest pigment values. TPC was highest in ungrafted plants (2.704 mg GAE·100 g<sup>-1</sup> DW), significantly exceeding Rezistar F1 (2.509 mg GAE·100 g<sup>-1</sup> DW) and *S. sylvatica* (2.521 mg GAE·100 g<sup>-1</sup> DW);  $p \leq 0.05$ . In contrast, the DPPH assay revealed the highest antioxidant capacity in fruits grafted onto *S. sylvatica*, whereas the ABTS assay showed no significant differences among treatments. Rootstock also strongly influenced pigments: ungrafted plants had the highest chlorophyll a (3.631 mg·100 g<sup>-1</sup> DW) and chlorophyll b (4.972 mg·100 g<sup>-1</sup> DW), whereas Rezistar F1 had the lowest values (2.100 and 2.657 mg·100 g<sup>-1</sup> DW, respectively). Lycopene was highest in ungrafted plants (1.667 mg·100 g<sup>-1</sup> DW) and lowest in Rezistar F1 (0.885 mg·100 g<sup>-1</sup> DW). Tannins varied modestly across grafting treatments but differed significantly ( $p \leq 0.05$ ). Collectively, these findings suggest that ungrafted plants favor pigment and lycopene accumulation, while *S. sylvatica* enhances DPPH radical scavenging activity.

**Table 2.** Fruit-quality attributes of grafted and non-grafted eggplant plants.

| Graft | TPC (mg<br>GAE·100 g <sup>-1</sup><br>DW) | ABTS (mmol<br>TE·100 g <sup>-1</sup><br>DW) | DPPH (mmol<br>TE·100 g <sup>-1</sup><br>DW) | Chl. a<br>(mg·100 g <sup>-1</sup><br>DW) | Chl. b<br>(mg·100 g <sup>-1</sup><br>DW) | Lycopene<br>(mg·100 g <sup>-1</sup><br>DW) | Tannins (mg<br>CE·100 g <sup>-1</sup><br>DW) |
|-------|-------------------------------------------|---------------------------------------------|---------------------------------------------|------------------------------------------|------------------------------------------|--------------------------------------------|----------------------------------------------|
| NG    | 2.704 ± 0.038 a                           | 0.964 ± 0.025                               | 1.171 ± 0.006 b                             | 3.631 ± 0.040 a                          | 4.972 ± 0.081 a                          | 1.667 ± 0.015 a                            | 0.107 ± 0.002 a                              |
| RF1   | 2.509 ± 0.045 b                           | 0.977 ± 0.009                               | 1.232 ± 0.008 a                             | 2.100 ± 0.022 c                          | 2.657 ± 0.008 c                          | 0.885 ± 0.011 c                            | 0.107 ± 0.001 a                              |
| SS    | 2.521 ± 0.005 b                           | 1.026 ± 0.007                               | 1.240 ± 0.010 a                             | 2.858 ± 0.049 b                          | 3.918 ± 0.141 b                          | 1.290 ± 0.045 b                            | 0.097 ± 0.002 b                              |
| Sign. | *                                         | ns                                          | *                                           | *                                        | *                                        | *                                          | *                                            |

NG—non-grafted; RF1—Rezistar F1; SS—*Solanum sylvatica*. The values are presented as mean ± standard error of individual replicates. Within each column, ns—no statistically significant difference, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

### 3.3. Effect of Fertilization on Fruit Quality

Fertilization exerted a significant influence on most traits, with the exception of total phenolic content (TPC) and antioxidant activity, as indicated in Table 3. The TPC values did not demonstrate statistically significant differences among the various fertilization regimes ( $p > 0.05$ ). In contrast, the levels of assimilation pigments, lycopene, and tannins showed a significant response to the fertilization treatments. Chlorophyll concentrations showed significant differences; the unfertilized control produced the highest chlorophyll a (3.302 mg·100 g<sup>-1</sup> DW) and chlorophyll b (4.442 mg·100 g<sup>-1</sup> DW), whereas biological fertilization resulted in the lowest pigment values. Lycopene followed a similar pattern, with the highest level in the unfertilized control (1.474 mg·100 g<sup>-1</sup> DW) and the lowest in the biological regime (1.030 mg·100 g<sup>-1</sup> DW). Tannins were highest in the unfertilized

control (0.113 mg CE·100 g<sup>-1</sup> DW) and lowest under chemical fertilization (0.099 mg CE·100 g<sup>-1</sup> DW;  $p \leq 0.05$ ). Overall, the unfertilized treatment favored pigment, lycopene, and tannin accumulation.

**Table 3.** Biochemical parameters of eggplant fruits under different fertilization regimes.

| Fertilization | TPC (mg GAE·100 g <sup>-1</sup> DW) | ABTS (mmol TE·100 g <sup>-1</sup> DW) | DPPH (mmol TE·100 g <sup>-1</sup> DW) | Chl. a (mg·100 g <sup>-1</sup> DW) | Chl. b (mg·100 g <sup>-1</sup> DW) | Lycopene (mg·100 g <sup>-1</sup> DW) | Tannins (mg CE·100 g <sup>-1</sup> DW) |
|---------------|-------------------------------------|---------------------------------------|---------------------------------------|------------------------------------|------------------------------------|--------------------------------------|----------------------------------------|
| NF            | 2.599 ± 0.018                       | 1.003 ± 0.021                         | 1.245 ± 0.017                         | 3.302 ± 0.032 a                    | 4.442 ± 0.077 a                    | 1.474 ± 0.019 a                      | 0.113 ± 0.002 a                        |
| B             | 2.577 ± 0.025                       | 1.022 ± 0.017                         | 1.187 ± 0.020                         | 2.464 ± 0.013 d                    | 3.230 ± 0.008 c                    | 1.030 ± 0.022 d                      | 0.102 ± 0.001 b                        |
| O             | 2.544 ± 0.052                       | 0.973 ± 0.015                         | 1.201 ± 0.011                         | 2.651 ± 0.032 c                    | 3.625 ± 0.091 b                    | 1.251 ± 0.001 c                      | 0.102 ± 0.00 b                         |
| Ch            | 2.592 ± 0.009                       | 0.957 ± 0.007                         | 1.224 ± 0.003                         | 3.035 ± 0.013 b                    | 4.099 ± 0.110 a                    | 1.366 ± 0.025 b                      | 0.099 ± 0.00 b                         |
| Sign.         | ns                                  | ns                                    | ns                                    | *                                  | *                                  | *                                    | *                                      |

NF—unfertilized, B—biological, O—organic, Ch—chemical. The values are presented as mean ± standard error of individual replicates. Within each column, ns—no statistically significant difference, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

### 3.4. Interaction Effects of Cultivar × Grafting on Fruit Quality

The cultivar × grafting interaction significantly affected all traits (Table 4). Overall, Mirval, combined with either ungrafted plants or *S. sylvatica*, produced superior outcomes compared with the other treatment combinations, particularly in terms of pigment content. Black Pearl grafted onto Rezistar F1 or *S. sylvatica* generally exhibited lower values for several quality parameters, including TPC and chlorophyll a and b. TPC, in all combinations of Mirval, with grafted plants, had significantly higher values than Black Pearl samples. Antioxidant activity also varied significantly: Mirval × *S. sylvatica* exhibited the highest ABTS activity (1.047 mmol TE·100 g<sup>-1</sup> DW), whereas Mirval × ungrafted and Black Pearl × Rezistar F1 had the lowest (0.934 and 0.942 mmol TE·100 g<sup>-1</sup> DW, respectively). For DPPH, Mirval × Rezistar F1 and Black Pearl × *S. sylvatica* showed the highest values ( $p \leq 0.05$ ). Pigment accumulation was strongly interaction dependent. Mirval × ungrafted showed the highest chlorophyll a (4.704 mg·100 g<sup>-1</sup> DW), chlorophyll b (6.651 mg·100 g<sup>-1</sup> DW), and lycopene (2.236 mg·100 g<sup>-1</sup> DW). The lowest pigment values were observed in combinations involving Black Pearl as well as Mirval × Rezistar F1. These results indicate that Mirval exhibits greater compatibility with ungrafted and *S. sylvatica* treatments, promoting higher pigment and lycopene accumulation compared with Black Pearl.

**Table 4.** Biochemical-quality parameters of eggplant fruits under cultivar × grafting interaction.

| Cultivar × Graft | TPC (mg GAE 100 g <sup>-1</sup> DW) | ABTS (mmol TE·100 g <sup>-1</sup> DW) | DPPH (mmol TE·100 g <sup>-1</sup> DW) | Chl. a (mg·100 g <sup>-1</sup> DW) | Chl. b (mg·100 g <sup>-1</sup> DW) | Lycopene (mg·100 g <sup>-1</sup> DW) | Tannins (mg CE·100 g <sup>-1</sup> DW) |
|------------------|-------------------------------------|---------------------------------------|---------------------------------------|------------------------------------|------------------------------------|--------------------------------------|----------------------------------------|
| MF1 × NG         | 2.956 ± 0.016 a                     | 0.934 ± 0.020 b                       | 1.176 ± 0.025 b                       | 4.704 ± 0.171 a                    | 6.651 ± 0.342 a                    | 2.236 ± 0.089 a                      | 0.112 ± 0.001 a                        |
| MF1 × RF1        | 2.919 ± 0.019 a                     | 1.012 ± 0.028 ab                      | 1.299 ± 0.011 a                       | 2.047 ± 0.028 d                    | 2.416 ± 0.030 d                    | 0.802 ± 0.016 d                      | 0.109 ± 0.001 ab                       |
| MF1 × SS         | 3.030 ± 0.011 a                     | 1.047 ± 0.005 a                       | 1.227 ± 0.004 ab                      | 3.569 ± 0.062 b                    | 5.150 ± 0.222 b                    | 1.708 ± 0.066 b                      | 0.094 ± 0.001 c                        |
| BPF1 × NG        | 2.453 ± 0.059 b                     | 0.993 ± 0.029 ab                      | 1.166 ± 0.013 b                       | 2.558 ± 0.091 c                    | 3.293 ± 0.180 c                    | 1.098 ± 0.059 c                      | 0.103 ± 0.004 abc                      |
| BPF1 × RF1       | 2.098 ± 0.072 c                     | 0.942 ± 0.009 b                       | 1.165 ± 0.005 b                       | 2.154 ± 0.017 cd                   | 2.897 ± 0.015 cd                   | 0.967 ± 0.006 cd                     | 0.104 ± 0.001 abc                      |
| BPF1 × SS        | 2.012 ± 0.002 c                     | 1.005 ± 0.019 ab                      | 1.253 ± 0.024 a                       | 2.146 ± 0.037 d                    | 2.687 ± 0.061 cd                   | 0.873 ± 0.023 cd                     | 0.100 ± 0.004 bc                       |
| Sign.            | *                                   | *                                     | *                                     | *                                  | *                                  | *                                    | *                                      |

MF1—Mirval F1; BPF1—Black Pearl F1; NG—non-grafted; RF1—Rezistar F1; SS—*Solanum sylvatica*. The values are presented as mean ± standard error of individual replicates. Within each column, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

### 3.5. Interaction Effects of Cultivar × Fertilization on Fruit Quality

The cultivar × fertilization interaction showed significant differences in all measured parameters (Table 5). Mirval generally exhibited stronger responses than Black Pearl across

fertilization regimes, particularly under chemical and organic fertilization. The cultivar  $\times$  fertilization interaction indicated that Mirval consistently exhibited the highest TPC across chemical, biological, and organic fertilization, whereas Black Pearl showed the lowest values under each fertilization regime ( $\leq 2.15$  mg GAE $\cdot 100$  g $^{-1}$  DW;  $p \leq 0.05$ ). ABTS activity was highest in Mirval  $\times$  organic (1.058 mmol TE $\cdot 100$  g $^{-1}$  DW) and Black Pearl  $\times$  unfertilized and biological (1.067 mmol TE $\cdot 100$  g $^{-1}$  DW), while Black Pearl  $\times$  organic and Black Pearl  $\times$  chemical showed the lowest ABTS values ( $\leq 0.894$  mmol TE $\cdot 100$  g $^{-1}$  DW). Pigment and lycopene values were markedly higher in Mirval  $\times$  chemical compared with Black Pearl  $\times$  chemical (chlorophyll a: 4.218 vs. 1.851 mg $\cdot 100$  g $^{-1}$  DW; chlorophyll b: 6.105 vs. 2.094 mg $\cdot 100$  g $^{-1}$  DW; lycopene: 2.039 vs. 0.694 mg $\cdot 100$  g $^{-1}$  DW). For tannins content, Black Pearl under unfertilized conditions had the highest value (0.120 mg CE $\cdot 100$  g $^{-1}$  DW), significantly exceeding that of Black Pearl under chemical fertilization (0.086 mg CE $\cdot 100$  g $^{-1}$  DW;  $p \leq 0.05$ ). Overall, Mirval benefited most from chemical and organic fertilization for pigment and lycopene accumulation, whereas Black Pearl showed a weaker response to fertilization.

**Table 5.** Biochemical-quality parameters of eggplant fruits under cultivar  $\times$  fertilization interaction.

| Cultivar $\times$<br>Fertilization | TPC (mg<br>GAE $\cdot 100$ g $^{-1}$<br>DW) | ABTS (mmol<br>TE $\cdot 100$ g $^{-1}$<br>DW) | DPPH (mmol<br>TE $\cdot 100$ g $^{-1}$<br>DW) | Chl. a<br>(mg $\cdot 100$ g $^{-1}$<br>DW) | Chl. b<br>(mg $\cdot 100$ g $^{-1}$<br>DW) | Lycopene<br>(mg $\cdot 100$ g $^{-1}$<br>DW) | Tannins<br>(mg CE $\cdot 100$ g $^{-1}$<br>DW) |
|------------------------------------|---------------------------------------------|-----------------------------------------------|-----------------------------------------------|--------------------------------------------|--------------------------------------------|----------------------------------------------|------------------------------------------------|
| MF1 $\times$ NF                    | 2.758 $\pm$ 0.012 b                         | 0.940 $\pm$ 0.003 bc                          | 1.211 $\pm$ 0.002 abc                         | 3.211 $\pm$ 0.010 b                        | 4.175 $\pm$ 0.078 b                        | 1.392 $\pm$ 0.030 bc                         | 0.106 $\pm$ 0.002 bc                           |
| MF1 $\times$ B                     | 3.007 $\pm$ 0.022 a                         | 0.974 $\pm$ 0.003 abc                         | 1.224 $\pm$ 0.025 abc                         | 3.191 $\pm$ 0.072 b                        | 4.185 $\pm$ 0.123 b                        | 1.325 $\pm$ 0.062 c                          | 0.099 $\pm$ 0.001 cd                           |
| MF1 $\times$ O                     | 2.998 $\pm$ 0.043 a                         | 1.058 $\pm$ 0.027 a                           | 1.229 $\pm$ 0.029 abc                         | 3.139 $\pm$ 0.118 b                        | 4.492 $\pm$ 0.219 b                        | 1.571 $\pm$ 0.019 b                          | 0.106 $\pm$ 0.002 bc                           |
| MF1 $\times$ Ch                    | 3.111 $\pm$ 0.047 a                         | 1.020 $\pm$ 0.016 ab                          | 1.271 $\pm$ 0.011 ab                          | 4.218 $\pm$ 0.073 a                        | 6.105 $\pm$ 0.293 a                        | 2.039 $\pm$ 0.074 a                          | 0.111 $\pm$ 0.001 b                            |
| BPF1 $\times$ NF                   | 2.439 $\pm$ 0.024 c                         | 1.067 $\pm$ 0.046 a                           | 1.280 $\pm$ 0.036 a                           | 3.393 $\pm$ 0.053 b                        | 4.710 $\pm$ 0.076 b                        | 1.555 $\pm$ 0.007 b                          | 0.120 $\pm$ 0.002 a                            |
| BPF1 $\times$ B                    | 2.147 $\pm$ 0.028 d                         | 1.071 $\pm$ 0.036 a                           | 1.150 $\pm$ 0.016 c                           | 1.737 $\pm$ 0.047 d                        | 2.274 $\pm$ 0.107 c                        | 0.737 $\pm$ 0.018 e                          | 0.106 $\pm$ 0.001 bc                           |
| BPF1 $\times$ O                    | 2.091 $\pm$ 0.062 d                         | 0.888 $\pm$ 0.003 c                           | 1.173 $\pm$ 0.008 bc                          | 2.163 $\pm$ 0.054 c                        | 2.758 $\pm$ 0.037 c                        | 0.932 $\pm$ 0.021 d                          | 0.098 $\pm$ 0.002 d                            |
| BPF1 $\times$ Ch                   | 2.073 $\pm$ 0.064 d                         | 0.894 $\pm$ 0.003 c                           | 1.176 $\pm$ 0.005 bc                          | 1.851 $\pm$ 0.048 cd                       | 2.094 $\pm$ 0.072 c                        | 0.694 $\pm$ 0.024 e                          | 0.086 $\pm$ 0.002 e                            |
| Sign.                              | *                                           | *                                             | *                                             | *                                          | *                                          | *                                            | *                                              |

MF1—Mirval F1; BPF1—Black Pearl F1; NF—unfertilized, B—biological, O—organic, Ch—chemical. The values are presented as mean  $\pm$  standard error of individual replicates. Within each column, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

### 3.6. Interaction Effects of Grafting $\times$ Fertilization on Fruit Quality

The grafting  $\times$  fertilization interaction significantly affected all traits (Table 6). TPC was highest in *S. sylvatica*  $\times$  unfertilized (3.108 mg GAE $\cdot 100$  g $^{-1}$  DW) and ungrafted  $\times$  organic (2.975 mg GAE $\cdot 100$  g $^{-1}$  DW), while the lowest value occurred in *S. sylvatica*  $\times$  organic (1.915 mg GAE $\cdot 100$  g $^{-1}$  DW;  $p \leq 0.05$ ). ABTS activity reached its maximum under Rezistar F1  $\times$  biological (1.125 mmol TE $\cdot 100$  g $^{-1}$  DW) and *S. sylvatica*  $\times$  unfertilized (1.084 mmol TE $\cdot 100$  g $^{-1}$  DW), whereas Rezistar F1  $\times$  chemical and Rezistar F1  $\times$  unfertilized showed the lowest ABTS values ( $\leq 0.903$  mmol TE $\cdot 100$  g $^{-1}$  DW). DPPH was highest in *S. sylvatica*  $\times$  unfertilized (1.366 mmol TE $\cdot 100$  g $^{-1}$  DW) and *S. sylvatica*  $\times$  chemical (1.360 mmol TE $\cdot 100$  g $^{-1}$  DW).

Pigment concentrations also differed substantially among treatment combinations. The highest chlorophyll a and b values were obtained in the ungrafted  $\times$  unfertilized control (4.409 and 5.938 mg $\cdot 100$  g $^{-1}$  DW, respectively) and ungrafted  $\times$  organic. In contrast, Rezistar F1 combined with organic or chemical fertilization resulted in the lowest pigment concentrations (chlorophyll a  $\leq 1.651$  mg $\cdot 100$  g $^{-1}$  DW; chlorophyll b  $\leq 1.961$  mg $\cdot 100$  g $^{-1}$  DW). Lycopene was highest in NG  $\times$  O (2.079 mg $\cdot 100$  g $^{-1}$  DW) and *S. sylvatica*  $\times$  chemical (1.948 mg $\cdot 100$  g $^{-1}$  DW), while the lowest level occurred in Rezistar F1  $\times$  organic (0.624 mg $\cdot 100$  g $^{-1}$  DW). Tannins were highest in NG  $\times$  O (0.121 mg CE $\cdot 100$  g $^{-1}$  DW) and lowest in *S. sylvatica*  $\times$  organic and *S. sylvatica*  $\times$  chemical (0.084 mg CE $\cdot 100$  g $^{-1}$  DW). Overall, ungrafted plants combined with organic fertilization increased total phenolic

content, lycopene, and tannins, whereas *S. sylvatica* under unfertilized conditions promoted higher antioxidant activity; Rezistar F1, particularly with organic or chemical fertilization, was associated with lower pigment and lycopene accumulation.

Table 6. Biochemical-quality parameters of eggplant fruits under grafting × fertilization interaction.

| Graft × Fertilization | TPC (mg GAE·100 g <sup>-1</sup> DW) | ABTS (mmol TE·100 g <sup>-1</sup> DW) | DPPH (mmol TE·100 g <sup>-1</sup> DW) | Chl. a (mg·100 g <sup>-1</sup> DW) | Chl. b (mg·100 g <sup>-1</sup> DW) | Lycopene (mg·100 g <sup>-1</sup> DW) | Tannins (mg CE·100 g <sup>-1</sup> DW) |
|-----------------------|-------------------------------------|---------------------------------------|---------------------------------------|------------------------------------|------------------------------------|--------------------------------------|----------------------------------------|
| NG × NF               | 2.345 ± 0.028 e                     | 1.023 ± 0.029 abcd                    | 1.232 ± 0.030 bcde                    | 4.409 ± 0.021 a                    | 5.938 ± 0.005 a                    | 1.958 ± 0.003 a                      | 0.106 ± 0.002 bcd                      |
| NG × B                | 2.613 ± 0.028 cde                   | 0.955 ± 0.047 de                      | 1.069 ± 0.014 fg                      | 2.481 ± 0.036 f                    | 3.368 ± 0.061 de                   | 1.127 ± 0.026 cd                     | 0.094 ± 0.002 de                       |
| NG × O                | 2.975 ± 0.113 ab                    | 0.969 ± 0.001 cde                     | 1.261 ± 0.016 abcd                    | 4.149 ± 0.047 b                    | 6.012 ± 0.140 a                    | 2.079 ± 0.012 a                      | 0.121 ± 0.006 a                        |
| NG × Ch               | 2.884 ± 0.019 abc                   | 0.908 ± 0.022 e                       | 1.120 ± 0.006 fg                      | 3.485 ± 0.056 c                    | 4.569 ± 0.129 b                    | 1.505 ± 0.043 b                      | 0.109 ± 0.001 abc                      |
| RF1 × NF              | 2.3444 ± 0.030 e                    | 0.903 ± 0.005 e                       | 1.138 ± 0.009 defg                    | 3.239 ± 0.029 d                    | 4.468 ± 0.140 bc                   | 1.487 ± 0.032 b                      | 0.118 ± 0.002 ab                       |
| RF1 × B               | 2.378 ± 0.101 e                     | 1.125 ± 0.001 a                       | 1.283 ± 0.049 abc                     | 2.041 ± 0.073 g                    | 2.397 ± 0.123 fg                   | 0.781 ± 0.045 e                      | 0.104 ± 0.003 bcd                      |
| RF1 × O               | 2.743 ± 0.081 bcd                   | 0.991 ± 0.033 bcde                    | 1.316 ± 0.003 abc                     | 1.471 ± 0.003 h                    | 1.802 ± 0.020 g                    | 0.624 ± 0.007 e                      | 0.101 ± 0.002 cd                       |
| RF1 × Ch              | 2.570 ± 0.030 de                    | 0.889 ± 0.008 e                       | 1.191 ± 0.024 cdef                    | 1.651 ± 0.042 h                    | 1.961 ± 0.068 g                    | 0.646 ± 0.023 e                      | 0.104 ± 0.001 cd                       |
| SS × NF               | 3.108 ± 0.057 a                     | 1.084 ± 0.030 ab                      | 1.366 ± 0.029 a                       | 2.258 ± 0.045 fg                   | 2.921 ± 0.096 ef                   | 0.976 ± 0.022 d                      | 0.114 ± 0.004 abc                      |
| SS × B                | 2.739 ± 0.054 bcd                   | 0.987 ± 0.004 bcde                    | 1.209 ± 0.026 cde                     | 2.870 ± 0.075 e                    | 3.924 ± 0.086 cd                   | 1.184 ± 0.085 c                      | 0.108 ± 0.003 abc                      |
| SS × O                | 1.915 ± 0.037 f                     | 0.958 ± 0.014 de                      | 1.025 ± 0.046 g                       | 2.334 ± 0.053 f                    | 3.061 ± 0.114 e                    | 1.052 ± 0.016 cd                     | 0.084 ± 0.001 e                        |
| SS × Ch               | 2.321 ± 0.016 e                     | 1.074 ± 0.006 abc                     | 1.360 ± 0.009 ab                      | 3.968 ± 0.024 b                    | 5.768 ± 0.270 a                    | 1.948 ± 0.056 a                      | 0.084 ± 0.001 e                        |
| Sign.                 | *                                   | *                                     | *                                     | *                                  | *                                  | *                                    | *                                      |

NG—non-grafted, RF1—Rezistar F1; SS—*Solanum sylvatica*; NF—unfertilized, B—biological, O—organic, Ch—chemical. The values are presented as mean ± standard error of individual replicates. Within each column, \*—significant difference. For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

3.7. Interaction Effects of Cultivar × Grafting × Fertilization on Fruit Quality

The cultivar × grafting × fertilization interaction significantly affected all evaluated traits (Figure 1). The highest polyphenol concentration (3.610 mg·100 g<sup>-1</sup> DW) occurred under Mirval × ungrafted × organic fertilization, whereas the lowest values were observed in Black Pearl combinations involving *S. sylvatica* × organic fertilization (Figure 1a). ABTS activity was maximal in Mirval × *S. sylvatica* × chemical (1.224 mmol TE·100 g<sup>-1</sup> DW) and Mirval × Rezistar F1 × biological (1.178 mmol TE·100 g<sup>-1</sup> DW), while Black Pearl × Rezistar F1 × chemical showed the lowest value (0.796 mmol TE·100 g<sup>-1</sup> DW) (Figure 1b). DPPH activity peaked in Black Pearl × *S. sylvatica* × unfertilized (1.523 mmol TE·100 g<sup>-1</sup> DW) and Mirval × Rezistar F1 × biological (1.475 mmol TE·100 g<sup>-1</sup> DW), whereas Mirval × ungrafted × biological had the lowest value (0.916 mmol TE·100 g<sup>-1</sup> DW) (Figure 1c).

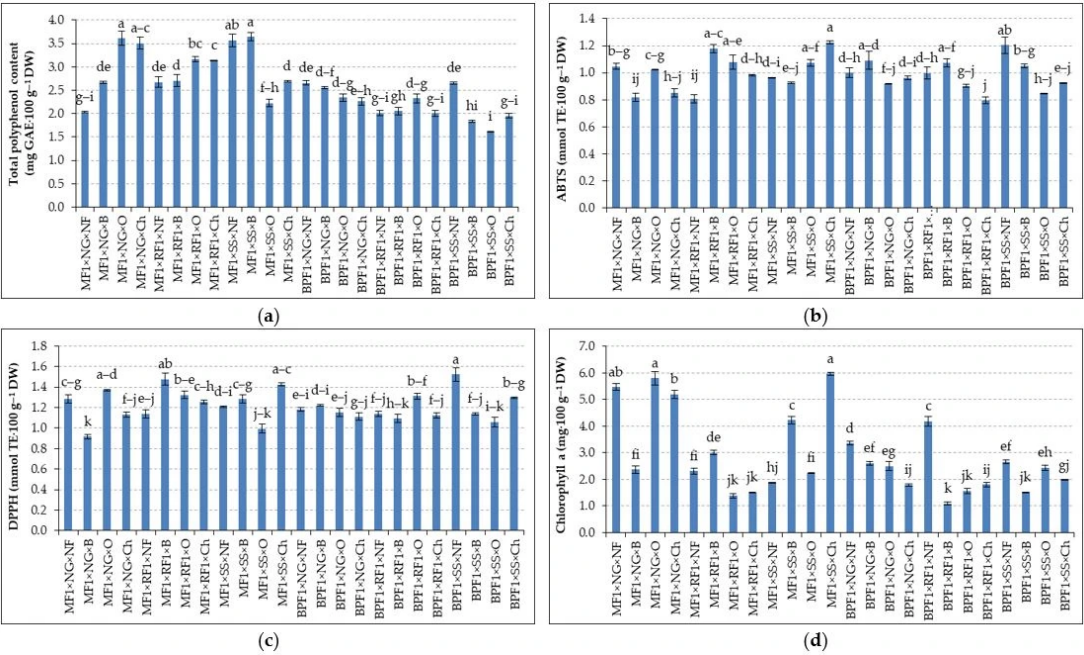


Figure 1. Cont.

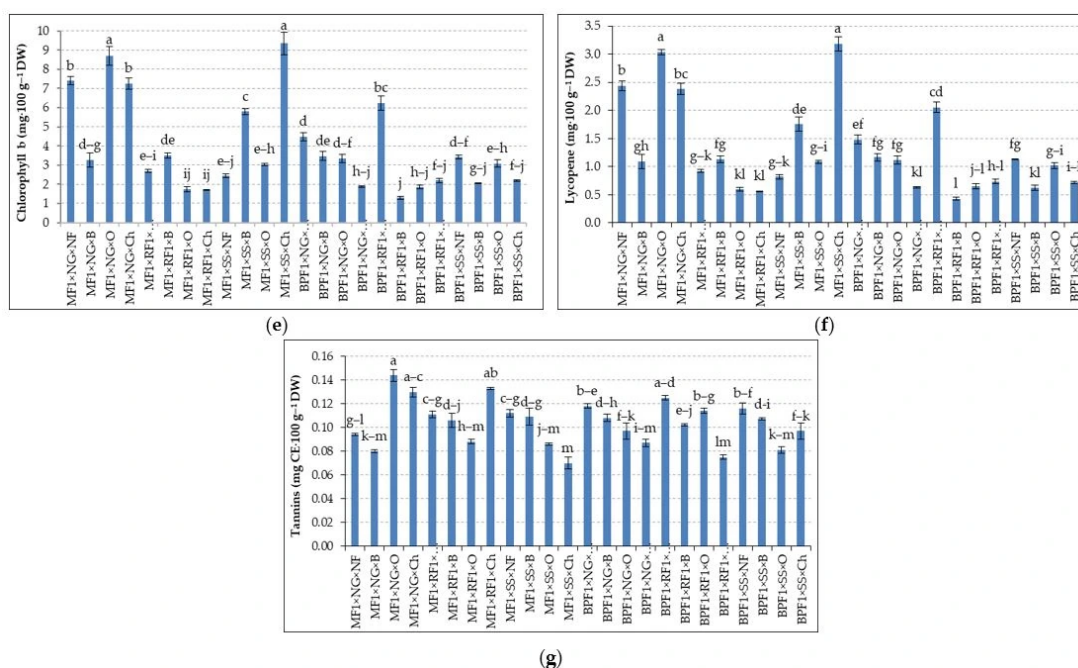


**Figure 1.** Effect of cultivar × grafting × fertilization on eggplant quality traits: (a) total polyphenol content; (b) ABTS; (c) DPPH; (d) chlorophyll a; (e) chlorophyll b; (f) lycopene; and (g) tannins. MF1—Mirval F1; BPF1—Black Pearl F1; NG—non-grafted; RF1—Rezistar F1; SS—*Solanum sylvatica*. NF—unfertilized, B—biological, O—organic, Ch—chemical. Bars represent means ± SE (n = 3). For each parameter, the letter “a” corresponds to the highest value. Different letters indicate statistically significant differences according to Tukey’s test ( $p \leq 0.05$ ).

Pigment accumulation exhibited pronounced interaction effects (Figure 1d,e). The highest chlorophyll a and chlorophyll b levels were recorded for Mirval × *S. sylvatica* × chemical (5.964 and 9.343 mg·100 g<sup>−1</sup> DW, respectively) and Mirval × ungrafted × organic (5.802 and 8.686 mg·100 g<sup>−1</sup> DW). The lowest pigment levels occurred primarily in treatments involving Rezistar F1 under organic or biological fertilization. Lycopene content was highest in Mirval × *S. sylvatica* × chemical (3.180 mg·100 g<sup>−1</sup> DW) and Mirval × ungrafted × organic (3.036 mg·100 g<sup>−1</sup> DW), whereas Black Pearl × Rezistar F1 × biological showed the minimum concentrations (0.429 mg·100 g<sup>−1</sup> DW) (Figure 1f). Tannins also differed significantly, with the maximum value in Mirval × ungrafted × organic (0.144 mg CE·100 g<sup>−1</sup> DW) and the minimum value in Mirval × *S. sylvatica* × chemical (0.070 mg CE·100 g<sup>−1</sup> DW) (Figure 1g).

To provide a more detailed understanding of the statistical significance underlying these observations, treatment comparisons according to Tukey’s test for each factor (cultivar, grafting, and fertilization) are presented in Supplementary Tables S3–S5. These tables allow for a delineation of which specific treatment combinations differ significantly for each measured trait, clarifying the contribution of individual factors and their interactions to eggplant fruit quality. According to the Supplementary Data presented in Tables S3–S5, Mirval fruits generally exhibited the highest values for most quality parameters when ungrafted under organic fertilization or grafted onto *S. sylvatica* under chemical fertilization. In contrast, for BPF1, grafting onto *S. sylvatica* under unfertilized conditions promoted the greatest accumulation of TPC, ABTS, DPPH, and tannins, whereas chlorophyll a, chlorophyll b, and lycopene were favored by grafting onto Rezistar F1 under unfertilized conditions (Supplementary Tables S3–S5). Further comparisons across each factor confirmed that, in general, Mirval fruits had higher total polyphenols, ABTS, DPPH, chlorophyll a, chlorophyll b, lycopene, and tannins than Black Pearl, regardless of grafting or fertilization treatment.

Collectively, the three-way interaction indicates that Mirval achieves the highest nutritional and functional quality when combined with ungrafted or *S. sylvatica* treatments and organic or chemical fertilization, whereas Black Pearl combinations—particularly with Rezistar F1—tended to produce lower-quality fruit under the tested conditions.

### 3.8. Multivariate Analysis of Biochemical-Quality Parameters

The application of principal component analysis (PCA) to investigate patterns and relationships among various fruit-quality parameters and treatment combinations revealed that PC1 accounts for 50.21% of the total variation, PC2 for 20.04%, and PC3 for 17.88%. Notably, only these three components exhibited eigenvalues greater than 1, as shown in Table 7, indicating that they represent the primary sources of variation among the treatments. The loadings of individual traits on each component (Table 8) indicated that total polyphenols ( $r = 0.536$ ) and tannins ( $r = 0.599$ ) made the largest contributions to PC3, whereas ABTS ( $r = 0.496$ ) and DPPH ( $r = 0.581$ ) had the strongest influence on PC2. Additionally, chlorophyll a ( $r = 0.501$ ), chlorophyll b ( $r = 0.501$ ), and lycopene ( $r = 0.500$ ) were most prominent in PC1. These findings suggest that both antioxidant compounds and pigments are the primary drivers of the differences among treatments.

**Table 7.** Eigenvalues and explained variance of principal components for eggplant fruit biochemical-quality parameters.

| PC | Eigenvalue | Percentage of Variance (%) | Cumulative Percentage of Variance (%) |
|----|------------|----------------------------|---------------------------------------|
| 1  | 3.51466    | 50.21                      | 50.21                                 |
| 2  | 1.40286    | 20.04                      | 70.25                                 |
| 3  | 1.2518     | 17.88                      | 88.13                                 |
| 4  | 0.50255    | 7.18                       | 95.31                                 |
| 5  | 0.31545    | 4.51                       | 99.82                                 |
| 6  | 0.01121    | 0.16                       | 99.98                                 |
| 7  | 0.00148    | 0.02                       | 100.00                                |

**Table 8.** Loadings of eggplant fruit-quality traits on the first seven principal components (PC1–PC7) obtained from PCA.

| Trait             | PC1   | PC2    | PC3    | PC4    | PC5    | PC6    | PC7    |
|-------------------|-------|--------|--------|--------|--------|--------|--------|
| Total polyphenols | 0.276 | 0.267  | 0.536  | −0.708 | 0.252  | 0.017  | 0.007  |
| ABTS              | 0.211 | 0.496  | −0.542 | 0.087  | 0.637  | 0.057  | 0.008  |
| DPPH              | 0.291 | 0.581  | −0.221 | −0.092 | −0.719 | −0.055 | −0.013 |
| Chlorophyll a     | 0.501 | −0.274 | −0.049 | 0.050  | −0.073 | 0.772  | 0.259  |
| Chlorophyll b     | 0.501 | −0.280 | −0.064 | 0.036  | 0.018  | −0.161 | −0.799 |
| Lycopene          | 0.500 | −0.278 | −0.071 | 0.039  | 0.032  | −0.609 | 0.542  |
| Tannins           | 0.205 | 0.338  | 0.599  | 0.691  | 0.084  | −0.010 | −0.003 |

DPPH—antioxidant activity determined by 2,2-diphenyl-1-picrylhydrazyl method; ABTS—antioxidant activity determined by 2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method.

The 2D representation of PC1 vs. PC2 (Figure 2) displays a broad distribution of treatments across the plot, indicating significant variation in fruit-quality parameters among the different combinations of cultivar, grafting, and fertilization regime. The PCA biplot further demonstrated that lycopene, chlorophyll a, and chlorophyll b were closely correlated, as they were positioned in the same quadrant with positive loadings on PC1 and negative loadings on PC2, resulting in largely overlapping vectors. In contrast, the remaining parameters, which include total polyphenols, tannins, ABTS, and DPPH, are positioned with positive loadings on both PC1 and PC2. This indicates that these traits vary together, but independently from the pigment-related variables across the different combinations of cultivar, grafting, and fertilization treatments. The predominant positioning of treatments

involving BPF1 on the negative side of PC1 indicates lower levels of the analyzed compounds, whereas MF1 treatments exhibited positive PC1 values, corresponding to higher overall contents.

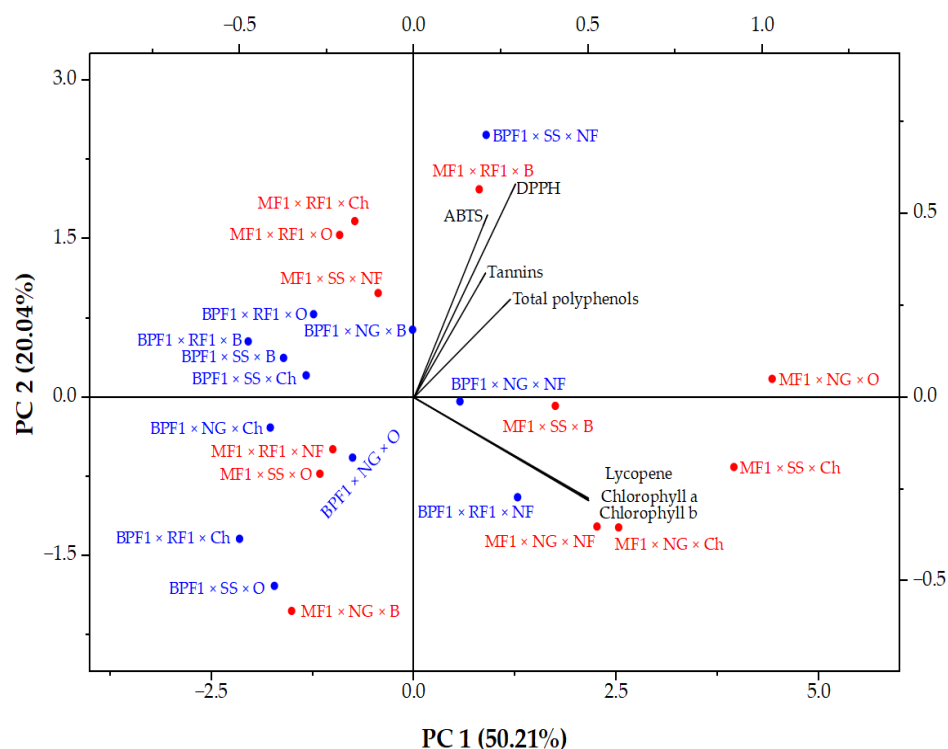


**Figure 2.** PCA biplot illustrating the distribution of experimental variants (red points for Mirval F1 and blue points for Black Pearl F1) in relation to eggplant fruit biochemical-quality parameters. MF1—Mirval F1; BPF1—Black Pearl F1; NG—non-grafted; RF1—Rezistar F1; SS—*Solanum sylvatica*; NF—unfertilized; B—biological; O—organic; Ch—chemical.

#### 4. Discussion

The present study demonstrates that the cultivar, grafting treatment, fertilization regime, and their interactions significantly influenced the nutritional and functional quality of eggplant fruits. These outcomes underscore the complex interplay between genotype and agronomic management in determining the accumulation of bioactive compounds and pigments under protected cultivation.

##### 4.1. Influence of Cultivar on Bioactive and Pigment Profiles

Mirval F1 consistently exhibited higher levels of total polyphenols, DPPH radical scavenging activity, chlorophylls, and lycopene compared to Black Pearl. This aligns with previous research showing that genotype strongly determines phenolic and carotenoid profiles in eggplant and other Solanaceae, with important effects on antioxidant capacity and health-related traits [31–33]. Phenolic and carotenoid compounds are associated with protection against oxidative stress and confer potential health benefits linked to reduced risk of chronic disease [34,35]. For example, cultivars with higher phenolic and carotenoid contents exhibit increased antioxidant capacity in both eggplant and pepper [36].

##### 4.2. Grafting Effects on Nutrient Allocation and Stress Response

Grafting significantly modulated fruit biochemical traits, particularly pigment content and antioxidant activity. Ungrafted plants produced fruits with higher chlorophyll and lycopene concentrations, whereas grafting onto *S. sylvatica* enhanced antioxidant activity. These results are consistent with studies showing that rootstock selection can influence

nutrient uptake, stress responses, and secondary metabolism in grafted vegetables [37,38]. Increased pigment concentrations in ungrafted plants may indicate more effective nutrient assimilation and source–sink relationships under our conditions. Enhanced antioxidant responses in *S. sylvatica* grafts might reflect rootstock-induced biochemical regulation via improved water relations or phytohormone signaling [39] or indicate stronger biochemical defense mechanisms. This is consistent with broader evidence that rootstock selection can modulate physiological and biochemical stress responses, including antioxidant mechanisms [10].

#### 4.3. Fertilization Regime and Secondary Metabolism

Fertilization regimes elicited contrasting responses in secondary metabolites and pigments. While TPC did not differ significantly across fertilization treatments, antioxidant activity, pigment content, lycopene, and condensed tannins showed significant variation. Higher pigment and tannin levels in unfertilized controls support the theory that mild nutrient limitation can activate the phenylpropanoid pathway and increase secondary metabolite production [40–42]. Microbial-based fertilization enhanced antioxidant activity (ABTS assay), suggesting that biological inputs can positively influence plant nutrient efficiency and antioxidant pathways [43–45]. The application of arbuscular mycorrhizal fungi, together with beneficial microorganisms, has been shown to improve eggplant (*Solanum melongena* L.) growth and fruit quality. These microorganisms enhance phosphorus and micronutrient uptake, stimulate root architecture, and activate antioxidant defense mechanisms, leading to increased phenolic compounds and improved antioxidant capacity and mineral composition of the fruits. In addition, microbial inoculation contributes to enhanced tolerance to abiotic stresses through the modulation of plant physiological and biochemical pathways [46,47]. In contrast, high levels of mineral fertilization favored primary growth processes, often at the expense of secondary metabolite accumulation [48–50].

#### 4.4. Interaction Effects and Optimized Management Strategies

Interactions among different cultivar, grafting, and fertilization regimes highlight the importance of integrative management approaches for improving eggplant fruit quality. The combinations Mirval  $\times$  *S. sylvatica*  $\times$  biological and Mirval  $\times$  Rezistar  $\times$  chemical were associated with the highest antioxidant activity and total polyphenol content among the tested treatments. Pigment contents, like chlorophylls and lycopene, were shown to be more significant for Mirval grafted on *S. Sylvatica* using chemical fertilization. Similar interactive effects have been observed in tomato and pepper, where specific scion–rootstock and nutrient combinations improved fruit quality and stress resilience [12,51,52]. These data can be attributed to the synergistic physiological effects induced by beneficial microorganisms. Involving AMF and PGPR enhances nutrient bioavailability, stimulates secondary metabolism, and activates antioxidant defense pathways. When combined with grafting, which itself modulates nutrient uptake efficiency and stress signaling, these effects may amplify phenolic biosynthesis and antioxidant accumulation in eggplant fruits. In contrast, chemical fertilization primarily supplies nutrients without inducing the same level of metabolic or defense-related stimulation. Similar increases in phenolic compounds and antioxidant capacity in biologically fertilized or microbially inoculated eggplant have been reported in previous studies [47,53].

Tannin content was higher in the ungrafted Mirval fertilized by the organic regime. This aspect can be explained as a stress factor, induced by the variety, on the proper roots.

Conversely, Black Pearl, under certain treatments, (e.g., grafted onto Rezistar F1 with organic or chemical fertilization) tended to produce lower biochemical values, suggesting that genotype  $\times$  management compatibility is critical when optimizing fruit quality under

protected cultivation. This aspect was clearly highlighted by the PCA analysis, which provided a comprehensive overview of the multivariate relationships and emphasizes how cultivar, grafting, and fertilization influence the quality of eggplant fruits. This pattern supports the hypothesis that compatibility between the scion genotype and rootstock, together with the fertilization system, plays a decisive role in modulating fruit biochemical composition under protected cultivation.

#### 4.5. Future Research

Despite providing valuable insights, this study has limitations: (1) it was carried out in a single greenhouse environment; (2) only a subset of fertilization regimes and doses were tested; and (3) yield vs. quality trade-offs were not quantitatively assessed.

Future research should address multi-season, multi-site validation, dose–response fertilization trials, systems biology analyses of metabolic regulation, and the integration of quality with yield outcomes.

The results highlight that combining high-performing cultivars (e.g., Mirval), compatible rootstocks (un-grafted or *S. sylvatica*), and targeted fertilization strategies (particularly organic/biological) can enhance eggplant functional quality, aligning with consumer demand for nutritious foods and sustainable production systems.

## 5. Conclusions

During the experiment, significant differences were observed according to variety, with Mirval F1 consistently showing higher levels of polyphenols, antioxidant activity, chlorophyll, lycopene than Black Pearl F1, highlighting the predominant role of genotype on determining the nutritional quality of the fruit. Grafting further modulated biochemical traits: un-grafted plants favored the accumulation of pigments and tannins, while grafting onto *S. sylvatica* improved antioxidant activity, indicating that rootstock selection can be used strategically to target specific functional attributes. Fertilization regimes also influenced fruit composition; moderate nutrient limitation favored the accumulation of secondary metabolites, while organic inputs improved antioxidant capacity. Mineral fertilization tended to reduce several bioactive compounds.

Strong interaction effects confirm that fruit-quality responses depend on the compatibility of cultivars, rootstocks, and fertilization regimes. Under the tested conditions, Mirval F1 combined with *S. sylvatica* grafting and biological or chemical fertilization showed the most favorable profile for antioxidant compounds and total polyphenol content, whereas ungrafted Mirval F1 under organic fertilization favored pigment and tannin accumulation. These findings highlight the importance of selecting compatible cultivar–rootstock–fertilization combinations for the targeted improvement of eggplant fruit quality.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae12081012/s1>, Table S1: Experimental variants resulting from the combinations of cultivar, rootstock, and fertilization treatments; Table S2: Results of a three-way ANOVA test demonstrating the interaction among the experimental factors; Table S3. Tukey’s HSD grouping of trait means by cultivar (95% confidence interval); Table S4. Tukey’s HSD grouping of trait means by rootstock (95% confidence interval); Table S5. Tukey’s HSD grouping of trait means by fertilization treatments (95% confidence interval).

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