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Yield Response and Antioxidant Activity of Greenhouse Organic Pumpkin (*Cucurbita moschata* Duch.) as Affected by Soil Solarization and Biofumigation

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Abstract: In intensive cropping systems, soil fumigation, i.e., the use of gas chemical pesticides applied to the soil covered with impermeable plastic film, represents an effective method to control most of the soilborne pests. However, its general non-selectivity to the useful soil microflora and microfauna together with their significant environmental problems has limited their use. Numerous studies have concerned the application of less impactful but, at the same time, equally effective disinfection methods. These are techniques with a low environmental impact that are particularly suitable for horticultural systems. Among these, both soil solarization and biofumigation are popular techniques, even in organic vegetable cropping systems. This paper reports the results of a study to evaluate the effects of soil solarization on the yield response and the antioxidant levels of organic pumpkin (*Cucurbita moscata* Duch.). Solarization was carried out alone and with the addition of some organic matrices, such as compost, manure and green manure species. The evaluation of the antioxidant activity was carried out with DPPH (1,1-diphenyl-2-picrylhydrazyl radical) assay: DPPH has a specific absorption band, which disappears in presence of an antiradical compound, showing its antioxidant capacity. Our results revealed that the pumpkins grown in solarized soil had IC_{50}, i.e., the concentration of sample which reduced the initial DPPH of 50%, values ranging between 0.6 to 18.0 mg mL^{-1}, lower than the values of IC_{50} of pumpkins grown in non-solarized soil, which ranged from 36.0 to 43.6 mg mL^{-1}. The obtained results highlighted the validity and utility of solarization for the organic vegetable crops. Furthermore, this technique has also shown its effectiveness in the long term since yield increases concerned several crops in succession. Finally, our results highlighted that heat treatment solarization can influence the level of several compounds in the pumpkin, and, therefore, also of the polysaccharides.

Keywords: weeds; bio-fumigation; yields; qualitative traits; antioxidants; green manure; amendments

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1. Introduction

In recent decades, many chemical fumigants, due to their negative environmental effects, have gradually being phased out [1]. Today, the number of registered fumigants is very low and there is a need for environmentally friendly strategies to control soilborne pests, i.e., pathogens, nematodes, weeds, arthropods, parasitic plants, etc., also in intensive cropping systems. Among the various non-chemical techniques for soil disinfestation, solarization and biofumigation by using amendments, such as green manure, crop residuals, manure, compost, etc., have become quite common among farmers [2].

Soil solarization is a technique in which the soil, moistened and mulched with a transparent plastic film, is heated by solar radiation for several days up to thermal levels lethal or injurious for soilborne pests [3]. On the other hand, biofumigation consists of soil solarization in which some organic matrix is added to have both the release of biocidal gases, such as alcohols, aldehydes, sulfides and isothiocyanates, resulting from the degradation of soil organic amendments, and to have some biostimulant or biofertilizer effects [4–6]. Both techniques are often used in vegetable cropping systems to ensure weeds and soilborne pests management and they are useful methods for soil disinfestation especially in organic farming [7].

The alimentary use of natural phenolic antioxidants has a positive correlation with lower cancer mortality, heart illnesses and longer life expectancy. These substances are responsible for strengthening immune function, inhibiting malignant transformation, and decreasing lipid peroxidation and DNA. Sick people need to consume foods with functional properties for the energy satisfaction and nutritional requirements. Vegetables, which contain bioactive components, able to reduce the risk of cardiovascular diseases, cancer, obesity and diabetes, are the cheapest and most easily obtainable source of nutrition [8]. The Cucurbitaceae family contains 130 genera and 800 species distributed in warm regions of the world. The family is cultivated everywhere in many environmental conditions [9].

Cucurbita moschata Duch. is an annual herbaceous crop, spread worldwide both for cultivation and consumption. It is known that *C. moschata* has a good content of beneficial nutrients, such as fiber, carotenoids, polysaccharides and other useful nutritional elements [10]. Between them, polysaccharides, considered important biological macromolecules, have an important role as antioxidant compounds being active as anti-diabetic, hypoglycemic, bacteriostatic, anticoagulant, and anticancer [11]. Therefore, pumpkin polysaccharides could be used as antioxidant in food as well as in the pharmaceutical industry.

This paper reports the results of a study that aimed to evaluate the long-term effects of both soil solarization and biofumigation on the agronomic response and antioxidant properties of a greenhouse organic cultivation of *C. moschata*.

2. Materials and Methods

2.1. Experimental Site Description and Experimental Design

Trials were undertaken in the countryside of Eboli (Salerno, Southern Italy) (40°34′ N, 15°01′ E, 38 m a.s.l.) in a farm producing organic vegetables. In particular, the experiment was carried out in a greenhouse without any active temperature control, having a metal structure covered by a multilayered made by low density polyethylene (LDPE) and ethylene vinyl acetate (EVA) diffusive plastic film with a thickness of 150 µm (Diffusive Suntherm C/929, Ginegar Plastic Product Ltd., Ginegar, Israel). The greenhouse, 40.0 m wide and 144.0 m long, had 20 spans (each one 40.0 m long and 7.2 m wide) and a 4.0 m^3 m^{-2} volume/surface index.

According to USDA, the soil, containing 23.6% sand, 33.7% silt and 42.7% clay, had a clay texture. The soil content of organic matter, pH, and electrical conductivity were 2.5%, 7.2, and 1.18 mS cm^{-1}, respectively.

2.2. Soil Solarization

Before solarization, the soil was carefully prepared at first, removing the residues of the previous crop, and afterward it was ploughed to 35 cm depth, uniformly rotavated and watered to field capacity at the same depth through a drip irrigation system with dripper lines 0.8 m apart and emitters (3 L h^{-1} water flow rate) spaced 0.25 m from each other.

The soil surface was then divided into two plots (7.2 × 30.0 m each) with a surface area of 216 m^2 per plot. Only the surface of one plot was then covered with a solarizing 35-µm-thick antifog transparent film (Polysolar C636, Polyeur S.r.l., Italy) and solarized for 55 days (from 29 June to 23 August 2018), whereas the other plot was kept uncovered. Both experimental conditions (solarized and non-solarized) were subjected to four different treatments (i.e., organic amendments): (1) manure (M); (2) compost (C); (3) green manure

(GM); (4) no amendment (Control). Therefore, a total of eight experimental treatments were provided, four solarized and four non-solarized, according to a split-plot block design, with three replicates. Solarized and non-solarized soil were placed in the main plots and the four amendment treatments in the 18 m^2 (7.2 m × 2.4 m) sub-plots.

During the solarization period, soil temperatures at 10 and 30 cm depth were monitored every 30 min by using PT-100 probes coupled with a CR- 10X data-logger (Campbell Scientific Inc., Logan, UT, USA). Moreover, during the trials, greenhouse air temperature and relative humidity were recorded, with a sampling interval of 30 min each day, by air temperature and relative humidity probes (CS500-L—modified version of Vaisala's 50Y Humitter, Campbell Scientific Inc., Logan, UT, USA) and data were recorded by a CR 10× data-logger (Campbell Scientific Inc., Logan, UT, USA).

At the end of solarization, a floristic assessment was carried out by classification, counting, and weighing of all weeds on sample areas of 1 m^2 per plot.

2.3. Amendments

A mixture of seven species, belonging to the Fabaceae, Brassicaceae, Boraginaceae and Graminaceae familes, was used for the green manure. In particular, the sowed species were: *Vicia sativa* L. (common vetch), *Vigna unguiculata* (L.) Walp. (cowpea), *Trifolium alexandrinum* L. (alexandrine clover), *Brassica juncea* L., (brown mustard), *Phacelia tanacetifolia* Benth. (phacelia), *Fagopyrum esculentum* Moench. (buckwheat) and *Sorgum bicolor* L. (forage sorghum). The sowing of the mixture was carried out on 16 April 2018 using 30 kg ha^{-1} of seed. The prevailing species was fodder sorghum followed by phacelia. The green manure had a pH of 8.1, 41.1% organic carbon and a C/N of 28.6. The dry biomass added with green manure was equal to 0.5 kg m^{-2}. The same amount of dry matter was calculated and applied for the other two amendments.

Manure amendment was carried out incorporating a dose of 25 kg m^{-2} of mature buffalo manure having 21% of dry matter, a pH of 8.5, 12.3% organic carbon and a C/N equal to 12.6.

For the compost amendment, an organic compost with 34.5% dry matter was applied with a dose of 1.5 kg m^{-2}. The used compost had a pH of 8.7, 28% organic carbon and a C/N of 5.6.

2.4. Crop Succession after the Solarization

After solarization, the experimental plots hosted three vegetable organic crops in succession. An autumn cycle of lettuce (*Lactuca sativa* L. var. *acephala* cv 'Othilie'), an autumn-winter cycle of kohlrabi (*Brassica oleracea* L. var. *gongylodes* cv 'Vikora') and a spring-summer cycle of pumpkin (*Cucurbita moschata* Duch. 'Butternut' cv 'Avalon F_1') were carried out. For all crops, the soil was mulched with a black plastic film.

2.5. Pumpkin Cultivation

For the cultivation of *C. moschata*, the soil, after having been freed from the residues of the previous crop (kohlrabi), was ploughed, milled, levelled and mulched with a black plastic film (50 μm thick LDPE). The transplant took place on 11 March 2019 using seedlings equipped with 3–4 true leaves following a planting layout of 0.9 cm × 2.4 cm to achieve a density of 0.46 plants m^{-2}. All the cultivation practices were those ordinarily performed by the growers of the Eboli area on the Pumpkin protected crop.

The Harvests took place from 7 to 11 June 2019 when the pumpkin peel presented the typical yellow-brown color. Then, the number and weight of all mature fruits in each plot were detected. In addition, the following characters were recorded on five random fruits per each plot: mean weight by an electronic balance (mod. CP4202S, Sartorius Co., Ltd., Goettingen, Germany), diameter (cm) and length (cm).

2.6. Antioxidant Activity

The antiradical activity was defined through the stable 1,1-diphenyl-2-picrylhydrazyl radical (DPPH), by the method of Brand-Williams et al. [12] with some changes [13]. In its radical form, DPPH has an absorption band at 515 nm, which disappears in presence of an antiradical compound. For preparation of the standard curve, different concentrations of DPPH methanol solutions (10–60 μg mL^{-1}) were utilized. The pumpkin samples (four grown in solarized and four grown in non-solarized plots) were centrifuged at 12,000× g for 15 min at 4 °C, as previously reported [14]. Then, the supernatant was collected for further analysis and it was properly diluted and added to a 1 mL of a methanolic DPPH solution (7.6×10^{-5} M), prepared daily. Methanol alone was employed as blank. A cuvette with 1 mL of DPPH solution (60 μM) was utilized as control. Absorbance at λ = 515 nm was revealed on a spectrophotometer Thermo scientifc Multiskan GO (Thermo Fischer Scientifc, Vantaa, Finland) after 15, 30 and 45 min. The DPPH concentration (mg mL^{-1}) in the reaction medium was measured from the calibration curve reported above and determined by linear regression (r^2: 0.9993): $y = 0.0008 + 0.0118x$. The IC_{50} value was defined as the concentration of sample which reduced the initial DPPH of 50%. All assays were carried out in triplicate and the results were expressed as the mean ± SD.

2.7. Statistical Analysis

Before performing analysis of variance (ANOVA), Shapiro–Wilk ($p \leq 0.05$) and Bartlett ($p \leq 0.05$) tests were applied to test normality and homogeneity of variances, respectively. Afterwards, data were subjected to the analysis of variance (two-way ANOVA) according to the split-plot experimental design, considering "soil solarization" and the "organic amendments" as sources of variation. Mean values were separated with the Student–Newman–Keuls (SNK) test, at the significance level of $p \leq 0.05$. Principal component analysis (PCA), a multivariate statistical technique that is able to extract information from a dataset, to express it as a set of new variables and to retain most of the variation in the dataset, was performed to evaluate correlation between non-solarized treatments and solarized treatments with some quantitative traits of pumpkin.

All statistical procedures were computed using the using the software RStudio: Integrated Development for R, version 2022.12.0+353.

3. Results

3.1. Soil Solarization

As shown in Table 1, all treatments at 10 cm depth had good number of hours at which the soil temperature was above 37 °C, a thermal value considered effective for the control of many telluric pathogens, fungi, nematodes, and weeds propagules [15]. On the contrary, at 30 cm depth, only the solarized plots recorded values above 37 °C, whereas the non-solarized plots had never exceeded that value. Therefore, the thermal treatment was effective at 10 cm since the soil warmed up sufficiently and for a suitable number of hours, but, on the other hand, at 30 cm depth the non-solarized plots had temperature levels too low (Table 1).

3.2. Yield and Morphological Traits

The ANOVA results showed significant effect of soil solarization and organic amendments, as well as their interaction on most of the pumpkin traits. No significant effect on fruits length was found whilst only a significant effect, i.e., soil solarization, for stem length was found (Table 2).

Table 1. Number of hours at different soil temperature range.

Temperature (°C)	Number of Hours							
	Treatments							
	Non-Solarized				Solarized			
	M	C	GM	Control	M	C	GM	Control
	10 cm depth							
<37	1027	1105	1102	806	54	38	180	95
≥37 and <42	291	213	216	322	557	486	477	483
≥42	0	0	0	190	709	795	662	741
	30 cm depth							
<37	1318	1318	1318	1318	78	60	75	60
≥37 and <42	0	0	0	0	1020	488	1006	600
≥42	0	0	0	0	222	775	239	660

Table 2. Effects of organic amendments and soil solarization on yield and some morphological traits of pumpkin.

Treatments [(1)]	Yield ($t\ ha^{-1}$)	Fruits Per Plant (n.)	Fruit Weight (kg)	Fruit Diameter (cm)	Fruit Length (cm)	Stem Length (cm)
Non-solarized M	28.83 ab	6.28 a	2.50 b	8.83 c	14.97	162.00
Non-solarized C	23.95 b	5.17 b	2.31 c	8.60 c	14.60	161.33
Non-solarized GM	27.14 ab	5.83 ab	2.45 b	8.10 e	14.70	160.33
Non-solarized Control	26.85 ab	5.70 ab	2.40 b	8.33 d	14.67	162.67
Solarized M	29.53 a	6.49 a	2.61 a	9.87 a	15.27	163.67
Solarized C	27.78 ab	6.04 a	2.49 b	9.27 b	15.03	166.67
Solarized GM	29.87 a	6.50 a	2.61 a	8.73 c	14.80	161.66
Solarized Control	27.90 ab	6.07 a	2.68 a	9.10 b	14.73	167.67
Significance [(2)]	*	**	**	**	ns	ns
Organic Amendments (A)						
M	29.18	6.38 a	2.55	9.35 a	15.12	162.33
C	25.50	5.60 b	2.40	8.93 ab	14.82	164.00
GM	25.50	6.17 ab	2.53	8.42 b	14.75	161.00
Control	27.37	5.88 ab	2.53	8.72 ab	14.70	165.17
Significance	ns	*	ns	*	ns	ns
Soil solarization (S)						
Non-solarized plots	26.69 b	5.74 b	2.41 b	8.47 b	14.73	161.58 b
Solarized plots	28.77 a	6.27 a	2.60 a	9.24 a	14.96	164.58 a
Significance	*	**	**	**	ns	*
Interaction						
A × S	*	**	**	**	ns	ns

[1] Mean values followed by a different letter are significantly different at $p \leq 0.05$, according to SNK test. [2] ns, no significant difference; *, Significance at $p \leq 0.05$; **, significance at $p \leq 0.01$.

With respect to pumpkin yield, the single effect of soil solarization was significant, whilst the single effect of the organic amendments was not (Table 2). Nevertheless, the interaction of soil solarization and amendments had a good significance. The combinations solarized plots having GM and M as amendments gave the best results, whereas the non-solarized plot amended with the C gave the worst yield (Table 2).

The number of fruits per plant had a good significance for all the monitored traits. Solarized plots had plants with a greater number of fruits compared to the non-solarized ones; moreover, the single effect of the organic amendments gave significative differences recording the M amendment as the best one followed by the C while the GM result was equal to the control one (Table 2).

Soil solarization was found efficient also for the fruit weight because the solarized plots had heavier fruit with respect to the non-solarized ones (Table 2). Though the organic amendments did not affect the fruit weight, the interaction between soil solarization and amendments was found highly significative (Table 2). The solarized plot amended with M, GM and the control gave the best results for fruit weight; on the contrary, the non-solarized C treatment had the fruit weight lower value (Table 2).

Fruit diameter was affected both by soil solarization and amendments as solarized plots had best results respect to the non-solarized ones, and between amendments M resulted the best amendment followed by C, control and GM (Table 2). The solarized plot amended with M was the best combination; on the other hand, the non-solarized plot amended with GM was the worst one (Table 2).

Fruit length was not affected by soil solarization or by amendments since no significative difference between treatments were found (Table 2).

Stem length data showed non significative differences between traits except for the single effect of soil solarization (Table 2).

3.3. Antioxidant Activity

With respect to antioxidant potential, the single effect of soil solarization was significant: in solarized control sample, the IC_{50} = 0.75 mg mL^{-1} was significantly lower than IC_{50} = 47.10 mg mL^{-1} of non-solarized control sample, after 15 min experimental time (Figure 1). The interaction of soil solarization and amendments had a good significance. The pumpkins grown in solarized plots, having GM and C as amendments, gave the best results with IC_{50} values of 0.55 and 2.05 mg mL^{-1}, respectively; on the other hand, the pumpkins grown in the non-solarized control plot showed the worst antioxidant potential with an IC_{50} = 43.60 mg mL^{-1} after 45 min experimental time (Figure 1). The pumpkins grown in non-solarized plots, having GM as amendment, gave the best value of IC_{50} between pumpkins grown in non-solarized plots. Therefore, the antioxidant effect was affected both by soil solarization and amendments: all four organic amendments in solarized plots, at all experimental times, showed a significant effect in comparison to four organic amendments in non-solarized plots.

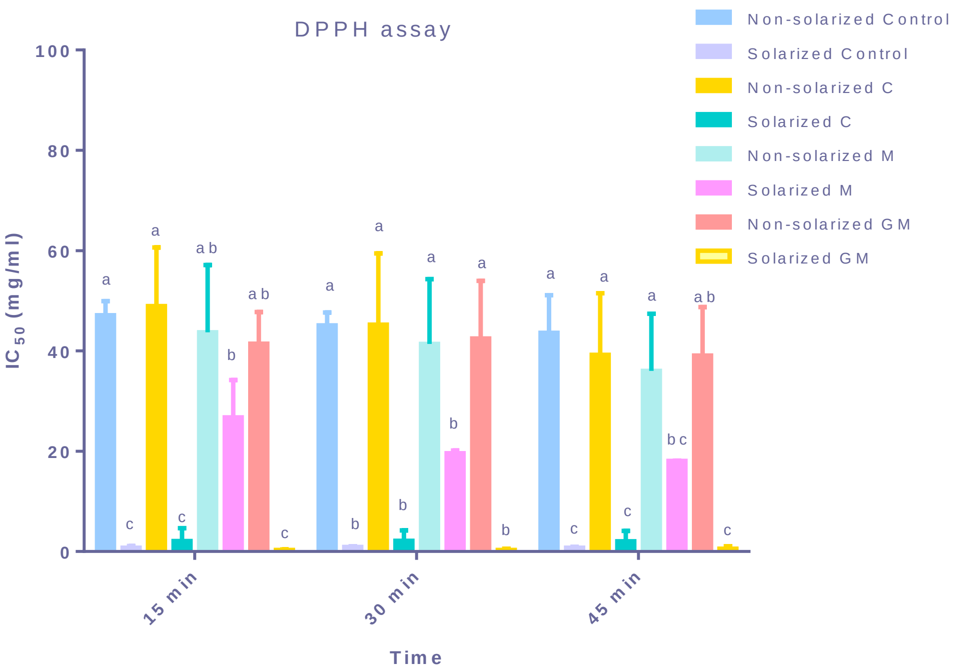

Figure 1. The antioxidant activity of four solarized samples and four non-solarized samples. Data are expressed as the mean of three experiments ± SD. Bars with different letters indicate mean values significantly different at $p \leq 0.05$, according to a two-way ANOVA followed by NSK test.

3.4. Principal Component Analysis

A principal component analysis (PCA) allowed a complete evaluation of the effects of technique of solarization and organic amendments on morphological, quantitative and antioxidant characteristics of pumpkin.

Eleven original variables were analyzed by employing PCA, and were reduced to two principal components, which represent 84.02% of the total variability. In particular, the first component (PC 1) explains the 66.54% of the total variability, and the second one (PC 2) explains for the 17.48% (Table 3).

Table 3. Loadings of the significant variables on two first principal components from data analysis.

Variables	Principal Components	
	1	2
Yield	0.8834	−0.4366
Fruits per plant	0.9165	−0.3873
Fruit weight	0.8761	−0.0448
Fruit diameter	0.8139	0.4295
Fruit length	0.8321	0.0432
Stem length	0.5193	0.7611
IC_{50} at 15 min	−0.8751	0.4232
IC_{50} at 30 min	−0.9084	0.3723
IC_{50} at 45 min	−0.9061	0.3724
Eigenvalue	5.99	1.57
Total variance (%)	66.54	17.48

PC 1 was highly and positively correlated with yield, fruits per plant, fruit weight, fruit diameter and fruit length. As shown in Figure 1, these variables were placed far from the origin of the first PC, and they were close together and then positively correlated. Instead, PC1 was negatively correlated with IC_{50} at 15, 30 and 45 min. PC 2 was positively correlated with stem length (Table 3, Figure 2).

The correlation between variables was illustrated clearly in Figure 2, a positive one when the two vectors were positioned with an angle lower than 90° and a negative one when with an angle higher than 90°. The treatments non-solarized Control, non-solarized GM and non-solarized M were included in the upper left quadrant of the negative side of PC1 with the highest values of IC_{50}.

The positive side of PC1, which includes the solarized M and solarized GM treatments, was characterized by the highest morphological traits (fruit length, fruit diameter and fruit weight) and quantitative ones (fruits per plant and yield). In addition, the fruit yield was strongly correlated with the number of fruits per plant.

The lower left quadrant was characterized by non-solarized C treatment, which manifested the lowest morphological traits. In the lower right quadrant, there were two treatments solarized Control and solarized C which gave the highest value of stem length and lowest values of IC_{50}.

The score plot (Figure 3) highlights a good separation between treatments. In particular, the solarized treatments were characterized to be more productive and more antioxidant active than the second ones, all non-solarized and plotted in the negative side of PC1, which tended to be less efficient on pumpkin investigated traits. This is also confirmed by the biplot of loading and scores in which all the reported loadings are near the solarized treatments (Figure 4).

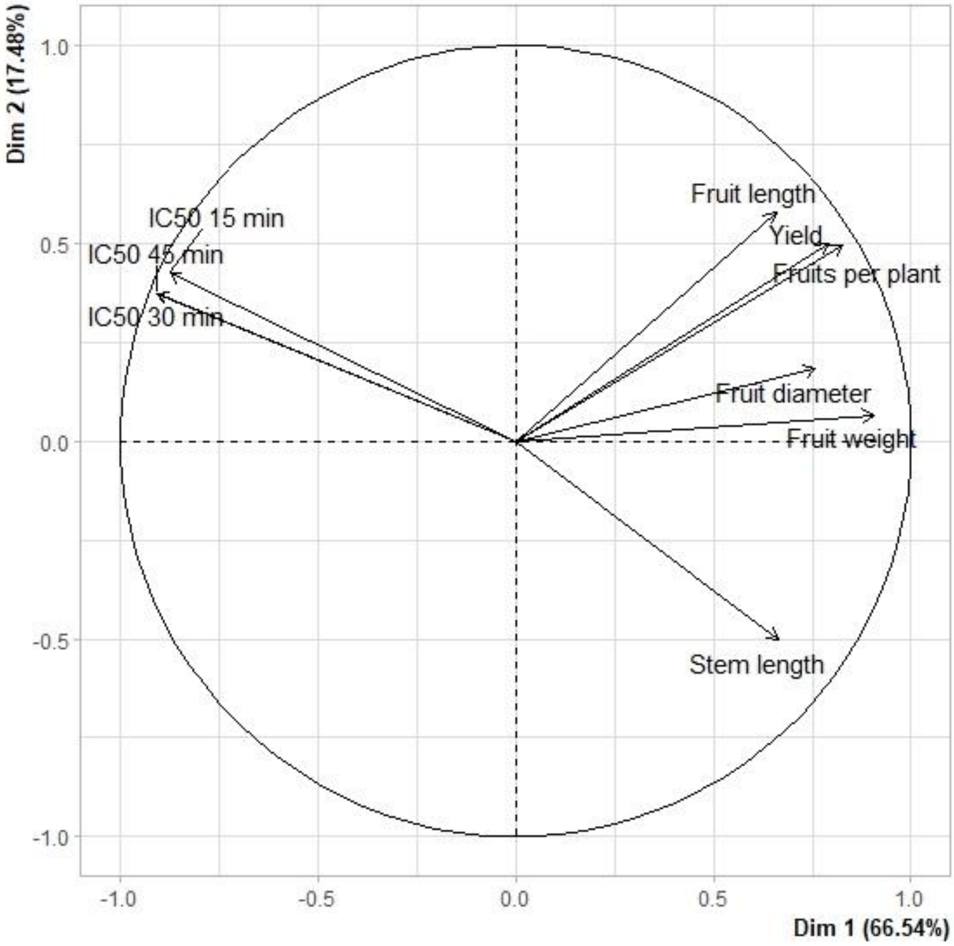

Figure 2. Loading plot of variables (yield, fruits per plant, fruit weight, fruit diameter, fruit length, stem length, IC_{50} at 15 min, IC_{50} at 30 min and IC_{50} at 45 min) in the two-dimensional space (Dim 1 = PC 1 and Dim 2 = PC 2).

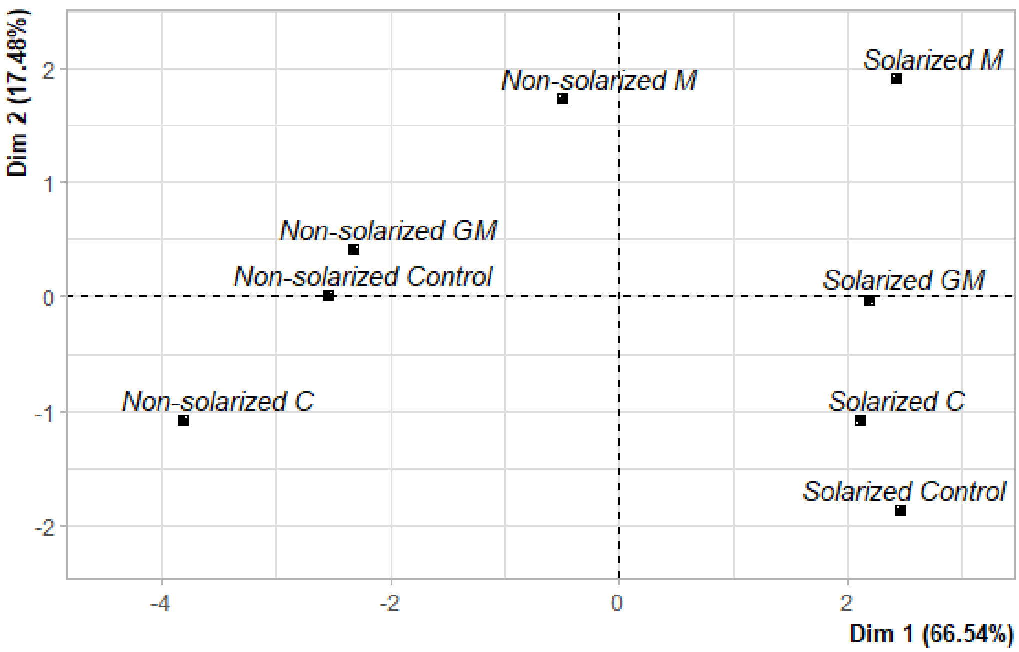

Figure 3. Score plot showing the projection of the treatments in the two-dimensional space.

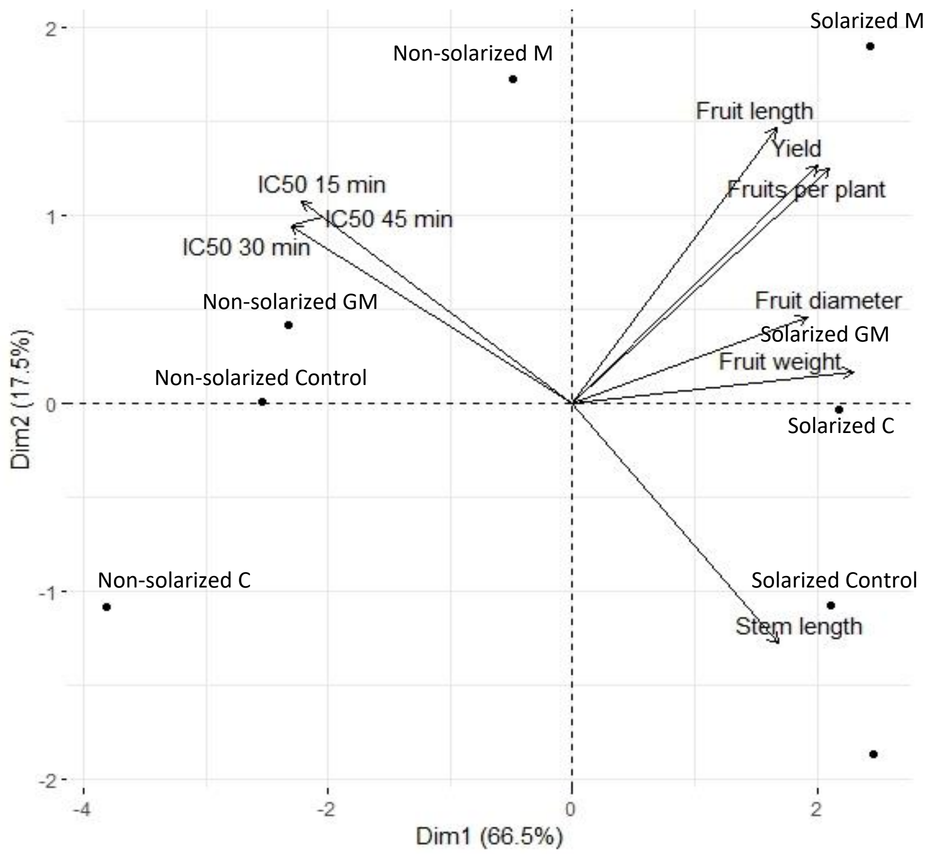

Figure 4. Biplot of loadings and scores in the two-dimensional space.

4. Discussion

The present study was conducted to evaluate the long-term effect of soil solarization, alone or coupled with organic amendments, on yield response and antioxidant activity of an organic pumpkin cultivation in greenhouse. The solarization treatment was conducted in the summer of 2018, while the pumpkin cultivation was carried out from March to July 2018 and, in the meanwhile, the other two crop cultivations, i.e., an autumn cycle of lettuce and an autumn-winter cycle of kohlrabi, were performed.

4.1. Soil Temperatures and Yield Response

Many soil biological, chemical and physical processes, such as soil structure, nutrient cycle, organic matter turnover, toxin accumulation and/or elimination and soil-borne pathogen suppression are driven by soil microorganisms and soil temperature [16–18]. Some soil proprieties, such as moisture, uptake of nutrients and water, microbial activities and seed germination can be altered by soil solarization [19,20]. This technique can result in a variation in the microbial community promoting the survival of thermo-tolerant microorganisms that can play an active role in pathogens suppression [21]. Furthermore, the use of organic amendments, rich in organic matter, can alter the soil C and N cycle having an effect to the microbial communities in the soil [22].

Moreover, some authors agreed that the increased yield response of solarization is not strictly disease-dependent, as also occurring in pathogen-free soils [23]. In particular, it is due not only to the suppression of weeds and soil pathogens, but also to a heat-induced release of soil nutrients [24–26]. In addition, some changes occurring in plant physiology, such as increased photosynthetic activity and protein levels, may cause the increased crop response of soil solarization [27].

In our study, to evaluate the presence of root-knot nematodes of the genus Meloidogyne, which are very dangerous to horticultural crops [28], a nematological analysis was carried out at the end of the solarizing treatment by the Coolen's flotation and centrifugation method [29]. As no nematodes were present at detectable levels, and because the two following crops were carried out in the autumn-winter season, a period not favorable to root-knot nematode attacks, the nematological analysis was repeated neither at the start of the pumpkin crop nor at its end, because no galls were observed on plants roots. Therefore, our findings on the positive effects of solarization treatment on the growth and yield of pumpkin are probably related to the release of nutrients induced by soil heat.

In our trials, during the soil solarization, for all the cover plots, the heating treatment reported good results both at 10 cm and 30 cm depth whilst only at 10 cm depth, it was not very efficient for the uncovered thesis. This result is very similar those obtained in other solarization treatments [30,31].

As reported by other authors [32–35], soil solarization has a good effect over time even after some vegetable crop cultivations.

Our data showed that the single effect of the solarizing treatment is significative and make the difference between the investigated thesis. This statement is also confirmed by the PCA biplot (Figure 4), in which there is a separation between non-solarized and solarized plots with a positive correlation between soil solarization and pumpkin yield.

Pumpkin quantitative traits and PCA (Table 2, Figure 2) put in evidence that solarized M and GM had the highest qualitative and qualitative traits, proving that manure and green manure favor the increase in soil fertility and its structure [36] and also having a good long-time effect on crop yield while the non-solarized theses, even if amended, have lower values than the solarized ones [37]. In particular the result obtained with the manure coupled to soil solarization agrees with some other studies that provide evidence that manure has a positive effect on plant growth mainly due to high availability of nutrients, bioactive substances, monosaccharides, free amino acids, vitamins and fulvic acid [38,39].

4.2. Antioxidant Activity

Recently, Akhter and coworkers [8] studied the antioxidant capacity, with the DPPH assay, of extracts of different parts (pulp, peel and seeds) of Cucurbitaceae plants, including *C. moschata*. They found that the antioxidant potential of these three parts was similar each other. Previously, Umavathi and coworkers [40] studied the antioxidant potential of pumpkin polysaccharides, extracted from dried pulp, and probably involved in the radical scavenging processes.

Rinaldi and coworkers [41] reported that the increase in total antioxidant capacity of pumpkin after a heat treatment (in that case related to cooking), similar to the heat treatment that occurs during the solarization process, could be attributable to the release of phytochemicals from cellular structures. The deep damage to cellular tissues, due to heat treatment, with the subsequent destruction of cell wall and compartments, determined the emission, in extracellular medium, of radical-scavenging antioxidant substances, such as carotenoids. Other authors [42] found that the antioxidant activities, evaluated by the DPPH assay, of *Cucurbita* samples show better results with increasing temperature.

The effect of solarization was evident in our study: in the literature, some reports were available on the possible effects of soil solarization treatment, alone or combined, to improve crop performance and plant nutritional and nutraceutical quality [43,44]. Fortis-Hernández and coworkers [45] studied the effects of different organic substrates, among which solarized bovine manure, on phytochemical features of *Solanum lycopersicum* L.; the authors reported that some of these treatments, mainly based on compost, induced a good antioxidant capacity. These data highlighted that several chemical substances, such as phenols, seem to be related to the production of antioxidants, which a plant can produce as defense method, in responding to oxidation stress.

5. Conclusions

The soil solarization treatment in a greenhouse, alone or with organic amendments, is confirmed to be a good alternative to chemicals even in vegetable crop succession having a strong long-time effect. In fact, pumpkin cultivation was the third crop after the heating treatment but, nevertheless, morphological, productive traits and antioxidant activity were positively affected by this technique. The use of organic amendments was positively supported by our results confirming especially for the manure the good combination with soil solarization. Nevertheless, organic amendments producing natural isothiocynates (ITCs) have to be managed carefully because the natural toxic ITCs share the same biochemical mechanism of action of the synthetic chemical ones against the target pathogens and/or pests. Therefore, the non-controlled use of natural ITCs may cause a vulnerability and instability of soil food webs and a suppression of beneficial soil organisms [46]. Therefore, further long-term trials are needed to reinforce findings on the positive interaction long-time effect of solarization and biofumigation on crop quantitative and qualitative traits.

The higher values of antioxidant activity, probably linked to the better emission of radical-scavenger substances by the damaged cells, give pumpkins grown in solarized soils a higher nutritional value. Indeed, the consumption of natural antioxidants in the diet has a positive correlation with good health and increased life expectancy; it has been strongly recommended to reduce the risk of oxidative stress and its related diseases.

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