

Article

Integrated Cover Crop and Fertilization Strategies for Sustainable Organic Zucchini Production in Mediterranean Climate

Francesco Montemurro ¹, Mariangela Diacono ¹, Vincenzo Alfano ^{1,*}, Alessandro Persiani ^{1,*}, Michele Mascia ², Fabrizio Pisanu ³, Elisabetta Fois ³, Gioia Sannino ⁴ and Roberta Farina ⁴

- ¹ Council for Agricultural Research and Economics, Research Centre for Agriculture and Environment (CREA-AA), Via Celso Ulpiani 5, 70125 Bari, Italy; francesco.montemurro@crea.gov.it (F.M.); mariangela.diacono@crea.gov.it (M.D.)
- ² Dipartimento di Ingegneria Meccanica, Chimica e dei Materiali, Università degli Studi di Cagliari, Via Marengo 2, 09123 Cagliari, Italy; michele.mascia@unica.it
- ³ Carbosulcis S.p.A., Località Nuraxi Figus, snc, 09010 Gonnese, Italy; pisanu.fabrizio@carbosulcis.eu (F.P.); fois.elisabetta@carbosulcis.eu (E.F.)
- ⁴ Council for Agricultural Research and Economics, Research Centre for Agriculture and Environment (CREA-AA), Via della Navicella 2-4, 00184 Rome, Italy; gioia.sannino@crea.gov.it (G.S.); roberta.farina@crea.gov.it (R.F.)
- * Correspondence: vincenzo.alfano@crea.gov.it (V.A.); alessandro.persiani@crea.gov.it (A.P.)

Abstract

The integration of different agroecological practices could significantly mitigate the impact of climate change. Therefore, a 2-year field experiment on organic zucchini was carried out to study the effects of clover (*Trifolium alexandrinum* L.) cover crop management (green manure, GM vs. flattening using a roller crimper, RC), compared to a control without cover (CT). This agroecological practice was tested in combination with the following different fertilizer treatments: T1. compost produced by co-composting coal mining wastes with municipal organic wastes compost plus urea; T2. compost produced with the same matrices as T1, replacing urea with lawn mowing residues; T3. non-composted mixture of the industrial matrices; T4. on-farm compost obtained from crop residues. The GM management showed the highest marketable yield and aboveground biomass of zucchini, with both values higher by approximately 38% than those recorded in CT. The T1, T2, and T3 treatments showed higher SOC values compared to T4 in both years, with a gradual increase in SOC over time. The residual effect of fertilization on SOC showed a smaller reduction in T3 and T4 than in T1 and T2, in comparison with the levels recorded during the fertilization years, indicating a higher persistence of the applied organic matter in these treatments. The findings of this study pointed out that combining organic fertilization and cover cropping is an effective agroecological practice to maintain adequate zucchini yields and enhance SOC levels in the Mediterranean environment.

Keywords: compost; roller crimper; green manure; agroecology; climate change; soil organic carbon (SOC)



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1. Introduction

The effects of climate change, such as rising temperatures and alterations in precipitation patterns, negatively impact the physical, chemical, and biological properties of the soil, thereby affecting soil fertility and crop yields [1]. In particular, different authors [2,3] reported that, in arid and semi-arid climates of Mediterranean areas, the hyper-thermic

conditions could cause rapid organic carbon mineralization with low humification rates, leading to a progressive depletion of soil organic matter (SOM).

In this context, the sustainable agricultural management practices that increase SOM content are essential to maintain and enhance both agricultural productivity and environmental quality [4]. Therefore, the integration of different agroecological practices could play a key role in adapting organic horticultural systems to climate change in Mediterranean environments [5].

Increasing resilience as an adaptation to climate change is a long-lasting process. Rather than focusing on a single factor, the potential synergistic effects of combined agroecological practices should thus be evaluated over the long term. This is because many biogeochemical processes, e.g., carbon sequestration in the soil, evolve slowly.

Among these practices, the organic fertilization can enhance the long-term resilience of agricultural systems by promoting healthy soils with active microbiota and favorable physical–chemical properties [6–8]. It has been pointed out by different authors [9,10] that using organic amendments obtained from agro-industrial wastes represents a win–win strategy to enhance soil health, recover nutrients, and, at the same time, reduce waste within a circular economy framework. For instance, both coal mining waste and the organic fraction of municipal solid waste are valuable sources of nutrients, since they are rich in humic substances. Despite the lack of direct fertilizing properties, coal mining waste can enhance both crop growth and yield through biostimulant and synergistic effects. This property is particularly evident when it is co-composted with the composted organic fraction of municipal solid waste [11].

Organic fertilization should not be considered as the unique strategy but should be integrated into a broader agroecological management approach, including cover crops and diversified crop rotations [12].

In crop rotations, the cover crops are planted either before a main crop as a break crop or intercropped as living mulch. In any case, their introduction into crop rotations can provide different beneficial ecosystem services, e.g., reducing nitrate leaching, improving soil physical properties, reducing soil erosion, and minimizing surface water runoff [13]. Therefore, the mitigation and adaptation to climate change may be additional important ecosystem services provided by cover crops [14]. As reported by different authors [15,16], cover crops can also affect greenhouse gas emissions from soil and increase soil organic C sequestration.

European organic farmers normally terminate cover crops by mowing or chopping them and then incorporating the plant materials into the soil through tillage (green manure, GM) before planting the cash crop [17]. Recently, termination by a roller crimper (RC), followed by direct cash crop transplanting into the cover crop residues, has attracted interest across Europe. It consists of flattening the cover crops, and therefore, it creates a mulch layer in contact with the soil. This practice can limit weed germination and improve the soil temperature and water content [18].

The methods used to terminate cover crops can affect both the nitrogen (N) mineralization and the N availability with cash crop demands [19,20]. In fact, incorporating plant residues into the soil as GM enhances decomposition and N release, whereas flattening the crop results in slower mineralization at the surface of no-tilled soils [16]. Several studies have evaluated RC as an alternative to traditional GM. However, the results on vegetable crop yields have been inconsistent, largely influenced by the cover/cash crop species and soil conditions [21].

The SOC is the most frequently reported parameter in long-term studies. It is considered the key indicator of agronomic sustainability of agricultural practices due to its influence on overall soil properties [6]. Thus, the evaluation of sustainable agricultural

management practices can be successfully achieved by agronomic performance analysis and SOC evaluation. This procedure can be considered a win–win approach. However, despite widespread recognition of the ecosystem services associated with cropping system diversification, to the best of our knowledge, there is a lack of information on the effectiveness of combining organic fertilization strategies with cover crop management to enhance SOC and crop performance. This lack is particularly evident for organic vegetable systems in Mediterranean environments, where zucchini is one of the main vegetable crops cultivated. Therefore, the objective of this research was to study the influence of different cover crop management strategies in combination with different organic fertilizers and amendments on an organic vegetable crop. To accomplish this goal, yield and soil organic carbon dynamics were thus assessed in a two-season organic zucchini field experiment.

2. Materials and Methods

2.1. Site Description, Field Experiment Setup, and Crop Measurements

The field experiment was carried out in 2022 and 2023 in one of the experimental farms of the Italian Council for Agricultural Research and Economics—Research Centre for Agriculture and Environment (CREA-AA), in Metaponto (MT), Southern Italy (lat. 40°24' N; long. 16°48' E, 8 m above sea level). The climate of the area is classified as accentuated thermo-Mediterranean, according to the authors of [22]. The soil is classified as “Epiaquet” [23], with a texture (at 0–0.5 m) of 60 and 36% of clay and silt, respectively, and an average bulk density of 1350 kg m^{−3}. The soil also has the following properties: low N (1.0 g kg^{−1}), 759 mg kg^{−1} of exchangeable potassium, and 31.1 mg kg^{−1} of available phosphorus. The organic matter is about 25 g kg^{−1}, the pH is 7.8, and the electrical conductivity is 0.48 mS cm^{−1}.

The field experiment was set up in a 2-year cauliflower–zucchini crop rotation with the same experimental design and crop management. The clover (*Trifolium alexandrinum* L. cv. Lorena) cover crop (berseem clover) was intercropped with the winter cash crop (cauliflower) and terminated before the zucchini (*Cucurbita pepo* L. var. President F1) transplanting. In this paper, we reported the two years of zucchini cultivation.

The experimental design was a split plot with two factors (cover crop and fertilization) and four replications in a completely randomized design. The main-plot factor was assigned to the cover crop management by comparing the following: (i) clover incorporated as green manure (GM); (ii) clover flattened by a roller crimper to create a mulch layer (RC); (iii) a control in which the clover was not sown (CT). In the latter treatment, the soil was tilled before zucchini transplanting.

The subplot factor consisted of four different fertilization treatments within each clover management system. Each elementary plot (combination of cover crop management × fertilizer treatment) consisted of a 2.5 m × 7 m (17.5 m²) area. In each season, the fertilization treatments were as follows: T1. compost produced by co-composting the coal mining wastes rich in humic substances (Carbosulcis S.p.A.) with a compost obtained from municipal organic wastes (Tecnocasic S.p.A.) and with urea; T2. compost produced by the same industrial matrices of T1, substituting the urea with lawn mowing residues; T3. non-composted mixture of coal mining waste with compost from municipal organic waste; T4. on-farm compost obtained from crop residues derived from previous horticultural cash crops cultivated in the experimental farm and grass clippings. We considered this treatment as a positive control, being largely adopted by the local organic farmers. More details on the materials utilized and composting processes are reported in the study of Diacono et al. [11].

In both years, the fertilizer treatments were applied in a single application about one month before zucchini transplanting. We adopted this procedure since the zucchini

cropping cycle is relatively short, and therefore, we considered the time of nutrient mineralization. In the CT plots, the fertilization rate was 100% of the normal N fertilization applied by farmers in the environmental conditions of the site (130 kg N ha^{-1}). Conversely, in the GM and RC treatments, the N rate was reduced to 75% ($97.5 \text{ kg N ha}^{-1}$) to account for the estimated N contribution from the leguminous cover crop (clover), based on its biological N fixation capacity. This reduction was defined according to previous studies and agronomic references, which report that clover cover crops typically contribute an average of about $30\text{--}35 \text{ kg N ha}^{-1}$ to the subsequent crop.

Clover was sown in the middle of September, a few days after the cauliflower was transplanted, and terminated before zucchini transplanting. It was sown at a rate of 35 kg ha^{-1} both in GM and RC on 10 and 13 September 2021 and 2022 for the 2022 and 2023 experiment years, respectively. The clover was intercropped with cauliflower and was ended at the first legume stage, i.e., when plants produced the first pods at the end of flowering. This stage occurred on 27 April and 29 May 2022 and 2023, respectively.

At termination, the aboveground biomass of the clover was measured using 0.25 m^2 sampling areas, and four samples were taken randomly from GM and RC plots. No significant difference in clover aboveground biomass was found between 2022 and 2023. On average over the two years, the total dry matter was $8.5 \pm 3.6 \text{ Mg ha}^{-1}$.

The zucchini was manually transplanted in three rows per plot with a spacing of $100 \times 60 \text{ cm}$, resulting in a plant density of about $1.7 \text{ plants m}^{-2}$. In 2022, the zucchini harvest started on 13 June and ended on 18 July. The entire cropping cycle consisted of 71 days. In 2023, the harvest started on 17 July and ended on 28 August, with the cropping cycle lasting 81 days.

At harvesting, which occurred at the commercial maturity stage (according to the local commercial standards), marketable zucchini fruits were collected from two randomly selected plants in each elementary plot. The fresh weight was recorded. To avoid potential contamination and/or border effects, the samplings were carried out in the middle of three rows of zucchini, maintaining a safe distance from the edges of each plot and the adjacent ones. After the final harvest, the aboveground plant biomass of the harvested zucchini was also weighed. Zucchini fruits and residues were oven-dried at 70°C for 48 h for dry weight determination.

2.2. Compost Piles Preparation and Composting Process

Two composting processes have been set up in a pilot plant of the experimental farm to recycle different wastes. In particular, the first compost was produced by co-composting the coal exhausted lye rich in humic substances (CLHSs), obtained by the process described in the European patent EP2449066B1 (Carbosulcis S.p.A., Gonnese (SU), Italy), with a compost from the selected organic fraction of municipal solid wastes collected in a treatment plant in south Sardinia (Tecnocasic S.p.A., Cagliari, Italy), and with urea (as N source). The second compost was obtained by co-composting CLHSs with compost from municipal solid wastes plus lawn mowing residues. Moreover, a non-composted mixture of raw CLHSs with the same compost was also prepared.

The raw materials were sampled and analyzed to determine their Total N and TOC contents (expressed in %). Their contents were determined by an elemental LECO analyzer (LECO, mod. RC-612; St. Joseph, MI, USA), using a dry combustion method. The percentage of each raw material used for the composting process was decided on a C/N ratio basis.

Each mixture of composting was manually prepared. The composting processes were carried out in static aerated piles (each about 1.2 and 1.8 m in height and base diameter, respectively) of about 750 kg. Once prepared, the composting piles were covered by

a non-woven sheet, to protect the materials both from solar radiation and rain, without preventing gas exchanges. The temperature was continuously monitored during the process with two probes connected to a data logger. These probes were positioned at different points of the pile. The moisture was weekly checked and kept at around 60%. To allow homogenization and correct degradation, the piles were manually turned with a shovel in a first stage, until the temperature decreased, indicating the end of the process. The obtained composts contained a N content of about 1.5% (dry matter) and had a C/N ratio of 23.

2.3. Weather Conditions

The mean monthly temperatures in the cultivation periods were similar to the long-term averages (Figure 1), except for June 2022 (25.8 °C compared to 22.5 °C in the long-term period) and July 2022 and 2023 (27.6 °C and 27.8 °C, respectively, compared to 25.2 °C in the long-term period). The cumulative rainfall from April to August was 92.8 mm and 239 mm in the first and second crop cycles, respectively. Therefore, the rainfall was lower by 31% and higher by 78% than the long-term values of the same periods.

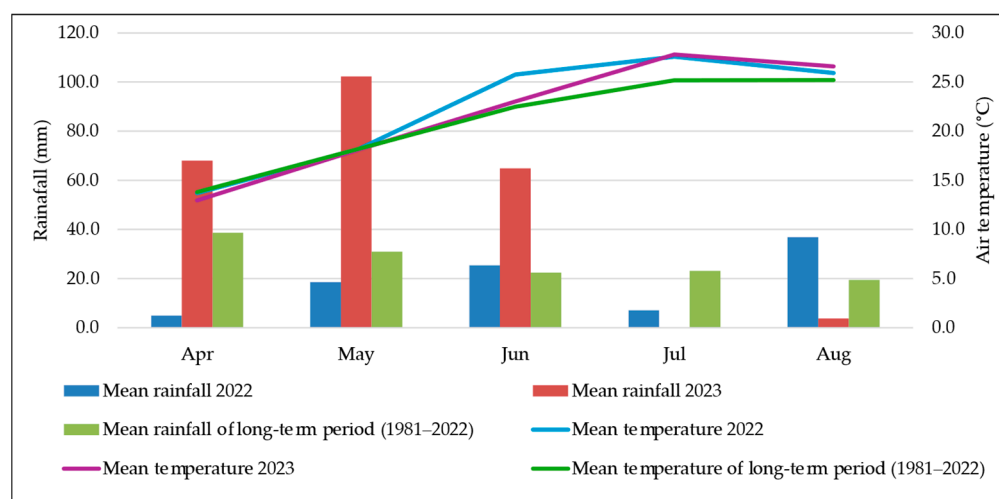


Figure 1. Mean monthly rainfall and temperature during the field experiment (May 2022–August 2023), in comparison with the long-term averages (1981–2022).

Furthermore, in the first cropping cycle, the monthly rainfall was on average lower by about 66% than the long-term mean rainfall of the same months, except for June and August 2022 (+13% and +90%, respectively). In the second cycle, from April to June, there was 235 mm of rainfall, while from July to August, there was only 4 mm (156% higher and 91% lower, respectively, than the long-term average).

The irrigation management was the same in all the analyzed treatments, and a drip irrigation system was adopted. The amount of irrigation water supplied was about 2500 and 3000 m³ ha^{−1} for the first and second year of zucchini cultivation, respectively. In particular, the irrigation was scheduled according to both plant needs and irrigation water availability (the water coming from the local consortium). Finally, the management of pests and pathogens was the same in all the plots and was in accordance with the European regulation for organic horticultural systems, even if the field experiment was not organically certified.

2.4. Soil Physical and Chemical Parameters

The samples for soil analysis were collected at 0–20 cm with a manual auger at the beginning of the experiment, in 2021, and repeated at the end of each crop cycle, namely, in 2022 and 2023. An additional sampling was taken in 2024, one year after the end of the experiment, to assess the residual effect of the fertilizers. The samples were air dried after removing all visible roots and coarse fragments (>2 mm) until reaching constant weight. Then,

they were sieved at 2 mm and stored at room temperature until analysis. Total organic carbon ($\text{g}\cdot\text{kg}^{-1}$) was measured using a LECO TOC Analyzer, mod. RC-612 (LECO Corporation, St. Joseph, MI, USA), and its concentration was turned into Mg ha^{-1} . On the same soil samples, the total concentration of heavy metals (ppm) was measured, by using Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES thermoscientific iCAP PRO, Thermo Fisher Scientific, Waltham, MA, USA), to assess any pollution risk. All the analyses were conducted in triplicate, and results were adjusted considering the water content of the soil.

2.5. SOC Dynamics Modeling After Organic Amendments

In this study, we used a non-linear model to simulate the dynamics of SOC over time for the different treatments. The approach followed a series of steps to estimate the decomposition rates of labile and stable carbon fractions (k_l and k_s , respectively). The initial carbon content (C_0), based on observed data, was further estimated. The observed SOC values for each treatment were collected over four years (2021–2024). These values were provided as the SOC content (in Mg ha^{-1}) for each year. The C inputs to the soil were measured and included organic fertilizers and plant residues.

A non-linear model was applied to describe the SOC dynamics over time, defined as follows:

$$C(t) = C_0 \times (f_l \exp(-k_l \times t) + f_s \cdot \exp(-k_s \times t)) + C_{\text{input}}$$

where

$C(t)$ is the soil organic carbon at time t ;

f_l and f_s are the fraction of labile and stable carbon, with $f_l = 0.70$ and $f_s = 0.30$, based on our measured values;

k_l and k_s are the decomposition rates for the labile and stable fractions;

C_0 is the initial carbon content;

C_{input} represents the input of carbon into the system each year.

The parameters k_l , k_s , and C_0 were estimated using a non-linear least squares (nls) regression approach. For each treatment, the model was fitted to the observed SOC values using the nls function in R (version 2024.04.1 Build 748). Initial guesses for the parameters were set as follows: $k_l = 0.5$, $k_s = 0.01$, and $C_0 = C_{\text{observed}}$. The parameter search was constrained within the bounds $0.1 \leq k_l \leq 2.0$, $0.0001 \leq k_s \leq 0.10$, and $10 \leq C_0 \leq 50$.

To assess the model performance and to compare measured and simulated values, we used the following statistical metrics:

RMSE (root mean square error), ranging from 0 to positive infinity, which indicates the accuracy of simulations. A value of 0 indicates a perfect fit of the modeled data to the measured data. The RMSE was expressed in the same unit as the measured data.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}$$

And R^2 (coefficient of determination) of the linear regression estimates versus measurements (association), ranging from 0 (absence of fit of the regression line) to 1 (perfect fit of the regression line): the closer the values are to 1, the better the model performance. Values <0.5 are considered not good, >0.5 are considered acceptable, and 0.8 is considered very good:

$$R^2 = \frac{\sum_{i=1}^n (P_i - O_i) \cdot (O_i - \bar{O})}{\sqrt{\sum_{i=1}^n (P_i - \bar{P})^2 \cdot \sum_{i=1}^n (O_i - \bar{O})^2}}$$

By fitting the model to the data and evaluating its performance, we estimated the key decomposition parameters k_l and k_s for each treatment, providing insights into the dynamics of carbon sequestration in soil under different management practices.

2.6. Statistical Analysis

A parametric analysis of variance (ANOVA) for the combined dataset of 2 years was performed. We considered the cover crop management and fertilizer as fixed factors and the year as the random factor. Before analysis, the Levene test was performed to assess the homogeneity of error variances, whereas the Kolmogorov–Smirnov and Shapiro–Wilk tests were computed to check the normality. The mean comparison was carried out according to the Duncan Multiple Range Test (DMRT) at a $p \leq 0.05$ probability level. Statistical analysis was carried out by using SPSS for Windows, Version 16.0, and R version 2024.04.1 Build 748. To quantify the residual effect of fertilization, the mean SOC of the fertilization years (2022–2023) was compared with the SOC in 2024 for each treatment. A paired t -test was conducted to assess statistical significance. Finally, the ANOVA was performed to evaluate treatment effects over time by using R (dplyr and ggpubr packages).

3. Results

3.1. Effect of Treatments on Crop Development and Yields

The analysis of variance showed significant main effects of year (Y) and cover crop management (C) on zucchini marketable yield and total aboveground biomass ($p < 0.001$) (Table 1). A significant interaction effect between year and cover crop management was also found for both analyzed parameters, with $p < 0.01$ and $p < 0.001$, respectively. Conversely, a significant interaction effect between fertilization and cover crop management was found only for the total aboveground biomass ($p < 0.05$). Finally, no interaction effects were found between year and fertilization among the three factors, for the analyzed parameters.

Table 1. ANOVA results.

	Marketable Yield (Mg ha ^{−1})	Total Aboveground Biomass D.M. (Mg ha ^{−1})
Year (Y)	***	***
Cover crop management (C)	***	***
Fertilization (F)	n.s.	n.s.
Y × C	**	***
Y × F	n.s.	n.s.
C × F	n.s.	*
Y × C × F	n.s.	n.s.

Note: n.s.: not significant. *, **, and *** significant differences at $p < 0.05$, 0.01, and 0.001, respectively. D.M.: dry matter.

The main effects of Y and C and their interactions are presented in Table 2. Since the interactions among the three factors were not significant, and according to the main significance of Y, we decided to present the C × F interaction, splitting the two years. The ANOVA results and values are reported in Figure 2.

Table 2. Zucchini marketable yield (fresh weight) and total aboveground biomass dry matter.

		Marketable Yield (Mg ha ^{−1})		Total Aboveground Biomass D.M. (Mg ha ^{−1})	
		Mean	DMRT	Mean	DMRT
Year (Y)					
	2022	25.03	a	2.88	a
	2023	6.40	b	1.15	b
		***		***	

Table 2. Cont.

		Marketable Yield (Mg ha ⁻¹)		Total Aboveground Biomass D.M. (Mg ha ⁻¹)	
		Mean	DMRT	Mean	DMRT
Cover crop management (C)					
	GM	19.03	a	2.32	a
	RC	14.29	b	2.04	b
	CT	13.84	b	1.68	c
		***		***	
Y × C					
2022	GM	29.39	a	3.28	a
2022	RC	25.40	b	3.23	a
2022	CT	20.31	c	2.13	b
2023	GM	8.66	d	1.37	c
2023	RC	3.18	e	0.86	d
2023	CT	7.36	d	1.24	c
		**		***	

Mean values in each column, followed by different letters, are significantly different according to the Duncan Multiple Range Test (DMRT). ***, $p \leq 0.001$; **, $p \leq 0.01$. (GM: green manure; RC: roller crimper; CT: control).

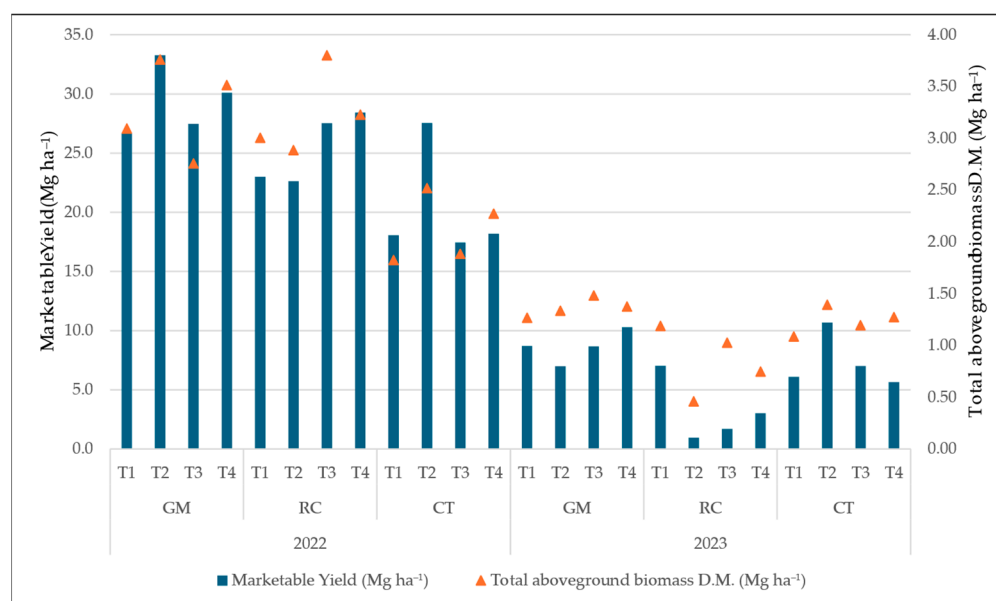


Figure 2. Interaction effects between cover crop management and fertilizer treatments on zucchini marketable yield and aboveground biomass D.M. (Mg ha⁻¹) at harvest in 2022 and 2023 (GM: green manure; RC: roller crimper; CT: control. T1. compost produced by co-composting coal mining wastes with compost from municipal organic wastes, plus urea; T2. compost produced by the same industrial matrices of T1, substituting the urea with lawn mowing residues; T3. non-composted mixture of coal mining waste with compost from municipal organic wastes; T4. on-farm compost from crop residues).

In the second cropping cycle, both the marketable yield and the total aboveground biomass were approximately 74 and 60% lower, respectively, as compared to the first cropping cycle.

Overall, GM treatments showed a marketable yield about 35% higher than the average of the RC and CT treatments, which did not differ significantly between them. The GM treatments also produced the highest aboveground biomass, followed by RC and CT treatments, with reductions of 12.1 and 27.6%, respectively.

In the first cropping cycle, the cover crop increased marketable yield by 44 and 25% in GM and RC, respectively, compared to CT. Marketable yield in GM was 15.7% higher than in RC. Finally, the average aboveground biomass in GM and RC treatments was higher by 34.7% compared to the CT one.

In the second cropping cycle, RC showed the lowest values for both parameters, which were 60.3 and 34.2% lower than the average of the GM and CT treatments, respectively.

3.1.1. Effect of Treatments on Soil Organic Carbon

The ANOVA showed significant main effects of both year (Y) and fertilizer treatments, while no significant effect of cover crop management was found for SOC accumulation.

The organic fertilizers applied to the soil induced different values of TOC, ranging from 149 to 440 g C kg⁻¹. The T1, T3, and T4 treatments showed an almost stable value of TOC across the two years, whereas for T2, it was 169% higher in the second year than in the first one (Figure S1).

Over the experimental years, the SOC pointed out significant trends across different fertilizer treatments and years (Figure 3). We found significant effects for the year ($p < 0.001$), fertilizer treatment ($p < 0.05$), and fertilizer $\times$ year ($p < 0.001$). In 2021, the initial SOC was very similar in all treatments, with T3 and T4 showing the average highest values. As shown in Figure 3, T1, T2, and T3 had higher SOC values in comparison to the T4 treatment both in 2022 and 2023, with a gradual increase over time.

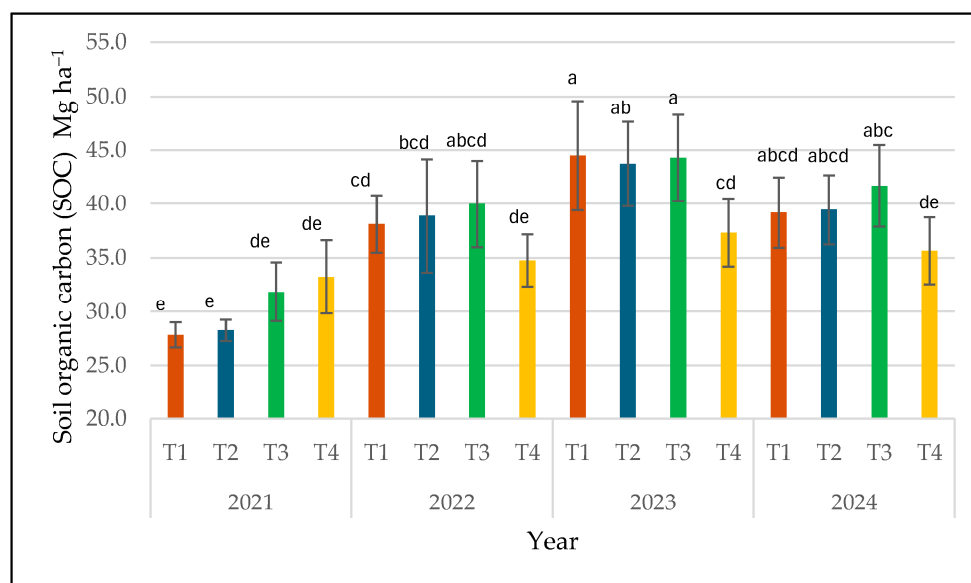


Figure 3. Soil organic carbon (Mg ha⁻¹) from 2021 to 2024 for the different fertilizer treatments. T1. compost produced by co-composting coal mining wastes with compost from municipal organic wastes, plus urea; T2. compost produced by the same industrial matrices of T1, substituting the urea with lawn mowing residues; T3. non-composted mixture of coal mining waste with compost from municipal organic wastes; T4. on-farm compost from crop residues. The letters above the bars represent statistically significant groupings based on the LSD (Least Significant Difference) post hoc test. Treatments within the same group, indicated by the same letter, do not significantly differ from each other. Treatments with different letters are significantly different at the $p < 0.05$ level.

The post hoc statistical analysis results, indicated by the letters in Figure 3, showed significant differences in SOC levels in the treatments and years. In particular, some

treatments presented stronger effects in specific years. Notably, treatment T4 consistently reached lower SOC levels across all years compared to T1, T2, and T3. However, the differences among the treatments were reduced over time, and this behavior is clear, especially in 2024, suggesting a stabilization of the SOC accumulation effect.

In 2022, all treatments except T4 had similar SOC levels, while in 2023 and 2024, the T4 treatment continued to show the lowest SOC values, followed by T1, T2, and T3.

On average, the organic amendments resulted in increases of 10.87, 10.62, 8.13, and 1.52 Mg SOC ha⁻¹ yr⁻¹ in 2022 and 6.37, 4.84, 4.30, and 2.59 Mg SOC ha⁻¹ in 2023 for T1, T2, T3, and T4, respectively.

The LSD post hoc test confirms significant statistical differences among the treatments in each year, with the grouping analysis indicating that treatment T4 was significantly different from the others, particularly in the later years. In 2024, T4 showed the lowest SOC value, while T1, T2, and T3 had the highest values, even though there was a gradual decline or stabilization of SOC over time.

The results of the analysis of the residual effect of organic fertilization on SOC indicated that there was a difference among treatments. In general, all treatments showed a decline in SOC in the last year (2024) compared to the fertilization years (2022–2023). In detail, the T1 and T2 treatments exhibited the highest SOC losses (−2.12 and −1.85 Mg C ha⁻¹, respectively), suggesting a lower persistence of the applied organic matter. T3 and T4 showed a smaller reduction (−0.46 and −0.39 Mg C ha⁻¹), indicating a more stable SOC content over time. However, in comparison to the first year, in 2024, SOC was higher on average by 37% in T1, T2, and T3 and only by 7% in T4.

In 2024, sorghum was cultivated in the entire experimental field to assess the residual effects of organic fertilizers. This practice allowed for the application of a two-pool decomposition model to simulate the dynamics of C in the soil. In the model, the C input to the soil is considered organic fertilizer and crop residues and cover crops.

The estimated parameters for the two-pool decomposition model, k_l and k_s , are presented in Table 3. These parameters were highly consistent across the first three organic amendments (T1, T2, and T3). They were significantly different from T4, which showed higher decomposition rates in both pools.

Table 3. Estimated parameters for organic amendments and plant residue degradation in the field experiment.

Organic Treatment	k_l (1/day)	k_s (1/day)	RMSE	R ²
T1	0.285	0.100	1.400	0.946
T2	0.215	0.100	2.257	0.843
T3	0.296	0.100	1.405	0.908
T4	0.605	0.038	0.824	0.693

Note: T1. compost produced by co-composting coal mining wastes with compost from municipal organic wastes, plus urea; T2. compost produced by the same industrial matrices of T1, substituting the urea with lawn mowing residues; T3. non-composted mixture of coal mining waste with compost from municipal organic wastes; T4. on-farm compost from crop residues.

3.1.2. Effect of Treatment on Heavy Metal Content in Soil

The values of heavy metals both in the composts applied and in the soil were always below the threshold values proposed by the Finnish Ministry of Environment (MEF, 2007) [24] and the World Health Organization (Figure 4). The concentrations of heavy metals in the soil ranged from 1.34 to 2.50 ppm for As (Arsenic) (average 1.96 ppm), 8.38 to 15.84 ppm for Pb (Lead) (average 8.71 ppm), 21.30 to 30.28 ppm for Ni (Nikel) (average 27.19 ppm), and 35.50 to 59.04 ppm for Cr (Chromium) (average 48.42 ppm). The Cd was either absent or below the detection limit of the analytical method used.

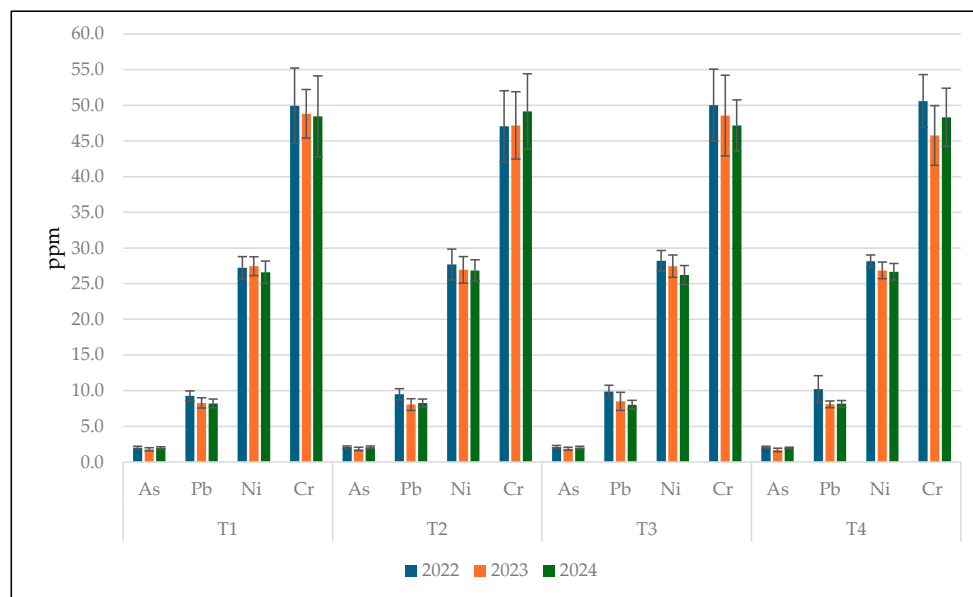


Figure 4. Total concentration of heavy metals (ppm) in different treatments (T1. compost produced by co-composting coal mining wastes with compost from municipal organic wastes, plus urea; T2. compost produced by the same industrial matrices of T1, substituting the urea with lawn mowing residues; T3. non-composted mixture of coal mining waste with compost from municipal organic wastes; T4. on-farm compost from crop residues). Vertical bars indicate standard errors. The orange, blue, and green bars represent the concentration of heavy metals in 2022, 2023, and 2024, respectively.

The ANOVA results showed that, for As, there was no significant effect for fertilizer (0.228), cover crop (0.495), year (0.225), and their interactions. This suggests no significant differences between treatments. For Pb, the year was highly significant (p -value < 0.0001), indicating that the Pb concentration changed significantly between years, with an increase in 2024. Fertilizer and cover crop were not significant, so there were no differences between treatments or covers in 2024 or in previous years. For Ni, the year was highly significant (p < 0.0001), indicating that its concentration differed significantly between years. Cr showed a significant effect for cover crop (p < 0.05), indicating that the introduction of cover in crop rotation influenced the Cr concentration. For this element, the year was not significant, so there were no significant differences between years.

4. Discussion

The strong effects observed for the factor of variation “year” were due to the variability in climate conditions between the two zucchini cropping cycles (Figure 1). Consequently, the significant reductions in marketable yield and aboveground biomass (74 and 60%, respectively) in 2023 compared to 2022 (Table 2) can be attributed mainly to climatic differences. Recently, Bentivenga et al. [25] pointed out that there has been an increase in extreme events, such as heavy rainfall and drought periods in the last twenty years in our study area (Metaponto plain), due to climate change and particularly to anthropogenic impact. The abundant and unusual spring rains that occurred in 2023 delayed zucchini transplanting by about a month. This delay caused difficulties in rooting and growth of the seedlings due to the high summer temperatures combined with an almost complete absence of rainfall, both in comparison to the first year and the long-term average. In particular, it should be noted that, although we tried to compensate for the lack of rainfall through irrigation, the water scheduling managed by the local consortium did not allow us to fully meet the crop’s evapotranspiration demands. Furthermore, the shift of the cropping cycle into the summer season during the second year further increased the plants’ water

requirements. Given these unusual conditions, our analysis will focus only on the first cropping cycle.

In 2022, the greatest marketable yield was obtained with the GM treatment. This result was due to the higher decomposition rate of the cover crops incorporated into the soil, which increased the available N content during the zucchini cropping cycle. The intermediate yields recorded in the RC treatment should be due to a slower rate of mineralization and N release from the flattened clover biomass. These findings are consistent with Parr et al. [26], who found that nutrient-release rates from residues left on the soil surface may be significantly lower than those from GM. Parr et al. reported that this behavior was due to reduced soil contact. In fact, the cover crop termination method can influence the soil-to-residue contact and the ability of soil microorganisms to decompose residues and release biomass N. In GM, the mowing or chopping residues increases the surface area available to decomposing soil microbes. This incorporation into the soil brings residues into close contact with the soil, accelerating decomposition and N release. Conversely, in RC systems, the residues left flattened on the soil surface limit microbial access, slowing N mineralization [19]. The CT treatment showed the lowest marketable yield, even if it received a fertilization rate of 100% of the N requirement for zucchini. In contrast, the increased marketable yield observed in GM and RC treatments, despite a 25% reduction in fertilization, confirms the contribution of clover's biological N fixation in enhancing soil fertility and boosting the yield of the subsequent cash crop in rotation [27,28].

Although the fertilization treatment did not have a significant effect on the parameters analyzed, its interaction with cover crop management was significant for total aboveground biomass production. This result highlights the importance of the introduction of cover crops in combination with organic amendments to enhance yields. The higher aboveground biomass production observed with the application of composted materials in GM pointed out the importance of the composting process compared to the use of the non-composted mixture. Conversely, the highest values recorded with the mixture in combination with RC, and the lowest values observed in the absence of cover, emphasized the key role of cover crops. These results support the findings of other authors, especially when leguminous crops are used both as living mulch [29] and break crops [30] in rotation.

Finally, we have to consider that CT treatment reached the lowest performance, and therefore, it is not sustainable in the long-term period. Conversely, the contribution of cover crops, in terms of nutrients together with the fertilizer strategy (one month before transplanting), could be a win-win situation for meeting zucchini's N needs and N release from organic amendment and cover crops mineralization. This is one of the most important issues in organic agriculture, especially in Mediterranean conditions, where the level of mineralization is relatively high.

Despite cover crops contributing approximately 60–75% to the total C input to the soil, their role in SOC stock buildup appears to be masked by the dominant influence of organic amendment application. Different authors [31,32], in similar pedoclimatic conditions, have reported that SOC increased by 0.3 to 1.1 t C ha⁻¹ yr⁻¹ when the cover crops were managed as RC or GM, respectively. However, in our study, the lack of a significant SOC accumulation for the cover crop management may be attributed to the rapid turnover of fresh plant material under Mediterranean conditions. The combination of high temperatures and soil moisture from crop irrigation (even if different for the two-year field experiment, as described before) likely accelerated decomposition, preventing long-term SOC stabilization [33,34]. In particular, as pointed out previously, the irrigation water was applied in both years (but it was successful for zucchini plant growth only in the first one), and the mean temperature in 2022 and 2023 was substantially higher compared to the mean temperature of the long-term period (Figure 1).

The effect of fertilization on SOC was influenced by the year. This result suggested that the different fertilizers may be more effective in specific years. This could be due to varying climatic conditions, soil moisture, or other yearly variations. It also implied that some treatments might have short-term or long-term effects that change over time.

In our experiment, among the organic fertilizers applied to the soil, the T4 treatment showed significantly lower SOC sequestration performance. This result can be attributed to the composition of the tested amendments, which were primarily derived from on-farm residues, mainly plant biomass. In silico studies have shown that organic amendments from crop residues undergo rapid decomposition, with values ranging between 27 to 58% of the C from crop-derived amendments in the first 30 days. This decomposition depends on the type of crops involved [35], which is consistent with the parameters of the decomposition model. In our experiment, the T1, T2, and T3 amendments presented the same materials, i.e., the coal mining wastes rich in humic substances and the municipal solid wastes, which are rich in humus-like substances [36]. Therefore, we expected the same decomposition range.

Considering the residual effect, the T1 and T2 treatments reached the highest SOC losses (-2.12 and -1.85 Mg C ha⁻¹, respectively) in 2024, despite their higher relative increase of SOC. This result suggested a lower persistence of the applied organic matter. Conversely, the T3 and T4 treatments showed a smaller reduction (-0.46 and -0.39 Mg C ha⁻¹), indicating a more stable SOC content over time.

The *t*-test results showed that none of the treatments had a statistically significant SOC change between the fertilization years and the last year ($p > 0.05$). However, T1 had the lowest *p*-value (0.143), suggesting a possible trend toward significance, although without reaching the threshold for statistical relevance. T3 and T4 reached the highest *p*-values (0.751 and 0.721, respectively), indicating that SOC remained relatively stable after fertilization ceased.

The absence of statistical significance for the residual effect of SOC in soil after fertilizer treatment was found. It would suggest that the SOC decline might be gradual and influenced by long-term decomposition dynamics rather than a sudden loss of carbon. The differences among treatments may be related to the stabilization potential of the organic materials applied, with T3 and T4 potentially contributing to longer-term SOC retention. Therefore, the findings of this research pointed out that the strategy of co-composting of the residue materials should be important from an agroecological point of view, not only for sustainable production but also for environmental sustainability (long-term SOC retention).

The simple two-pool models effectively capture SOC dynamics in soil and serve as a valuable tool for assessing SOC sequestration potential in similar materials, supporting carbon farming evaluations.

The content of heavy metals indicated that they did not pose a significant risk to either plant growth or public health. In general, their annual soil levels were not strongly influenced by fertilizer treatments but rather by yearly variability. However, a longer monitoring time will be necessary to detect any significant accumulation that can occur during continuous use of the tested organic matrices.

5. Conclusions

Our study pointed out the possibility of combining different agronomic strategies to achieve an adequate zucchini yield and improve SOC levels, thereby enhancing sustainability.

The introduction of cover crops in crop rotation increased the marketable yield of zucchini, with GM management showing the highest values. The CLHS-based fertilizer application determined an increase in SOC over time, while on-farm compost resulted in

the lowest values, although it showed a smaller reduction in the residual effect on SOC. This result would indicate a higher persistence of applied organic matter.

Our study suggests that the integration of different agroecological practices plays a key role in adapting organic horticultural systems to climate change in the Mediterranean environments, by improving soil fertility through enhanced SOC levels. However, as a two-year crop rotation period may not be sufficient to draw definitive conclusions, it is essential to highlight that additional studies are needed to fully evaluate the long-term effects of these practices.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/horticulturae11070809/s1>, Figure S1: Total organic carbon of the different treatments.

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Abbreviations

The following abbreviations are used in this manuscript:

GM	Green Manure
RC	Roller Crimper
CT	Control
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
TOC	Total organic Carbon
CLHS	Coal exhausted Lye rich in Humic Substances
RMSE	Root Mean Square Error
DMRT	Duncan Multiple Range Test
LSD	Least Significant Difference
Y	Year
C	Cover crop management
F	Fertilization

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