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Agronomic and Environmental Performances of On-Farm Compost Production and Application in an Organic Vegetable Rotation

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Abstract: Horticultural crops produce huge amounts of wastes due to the large difference between total and marketable yields, and plant residues. The biological stabilization and sanitization of these organic materials directly on-farm through a simple technique such as composting may be a feasible and sustainable management strategy. The objectives of this research were to (i) estimate the sustainability and the energy impact of the on-farm composting process; (ii) to evaluate the agronomic performance and sustainability of the compost application, compared to a commercial organic fertilizer; and (iii) to identify the management and environmental hotspots. To accomplish these aims, a composting process was set up and monitored using the organic wastes and residues produced in the experimental farm. The compost produced was compared to a commercial organic fertilizer in combination with the use of cover crops in the rotation, in a two-year pepper cultivation. All processes were assessed using an energy analysis and a carbon stocks and emissions evaluation. Our findings point out that the composting process on-farm was environmentally sustainable in terms of energy consumption and carbon emissions and produced a good quality fertilizer. The use of this compost determined the best agronomic performance, especially when it was combined with other agro-ecological techniques. The yield values were slightly higher and statistically comparable with the commercial fertilizer ones. Moreover, the treatments that included the compost were most energy efficient and showed the best compromise between C emissions and C stocks.

Keywords: agricultural wastes; on-farm compost; energy efficiency; carbon stocks; organic horticultural rotation

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1. Introduction

Conventional agriculture is characterized by high crop specialization (i.e., monoculture) with the subsequent biodiversity loss and agroecosystems simplification, the indiscriminate use of chemical inputs with high environmental pollution, the decrease in the soil organic matter (SOM) content and the increase in soil erosion and degradation. Therefore, this production method has been identified as "not sustainable" [1]. In this context, suitable solutions aimed at improving the agro-systems sustainability and effective techniques and methodologies at farm level are widely studied [2,3]. Among them, the recycling of agricultural wastes through on-farm composting can be considered valuable and sustainable [4], allowing us to produce an organic matter fertilizer, by reducing wastes and potential environmental pollutants [5]. In particular, in the Mediterranean area, horticultural farms must face the challenge of disposing of a huge amount of both no-marketable products and waste biomass resulting from crop residues [4], as well as addressing the issues of desertification and loss of soil organic matter [6].

Compost is a source of stabilized and humified organic matter, which can improve the chemical, physical and biological properties of cultivated soils. Different experiences carried out both in experimental sites [3] and directly on farms [7] in different conditions, showed that producing compost on-farm is economically/environmentally sustainable and quite easy. However, despite the numerous benefits of compost that are well known and widely studied, its production directly on a farm, particularly at a small farm scale, is still not a common management practice in the Mediterranean area.

A study conducted by Viaene et al. [8] reveals that the main barriers to on-farm composting are the lack of experience and farmers knowledge on both the composting process and medium/long-term benefits of compost application, as well as the often-complex regulations of the sector. Moreover, other studies have demonstrated that the composting method is not free from pollution problems [5]. The stages of a composting process, which have the potential to negatively affect the environment, include the selection of feedstocks, transport to and from the composting site, energy use during composting, gas emissions during degradation and the end use of compost products [9]. Thus, composting should be evaluated as any other agricultural techniques that may lead to both management and environmental issues.

The assessment of sustainability of farm-scale composting should focus on an evaluation of both the composting process and the effect of compost application. In general, different methods have been developed to assess the environmental performance of main agricultural activities. Among them, the energy analysis (EA) and the carbon footprint (CF) are the most used methods. An efficient use of energy resources is crucial when it comes to thinking of the most sustainable production systems [10]. The energy analyses reinforce the comprehension of the functioning of agricultural systems in technical-productive and economic decision-making processes and contribute to find viable energy alternatives in agriculture [11]. In addition to energy flow evaluation, the study of carbon footprint is an essential component of the environmental impact assessment of agricultural production [12]. The carbon footprint can be defined as the total amount of greenhouse gases (GHG) produced directly and indirectly by farming activities, usually expressed in tons of carbon dioxide equivalent (CO_2eq).

The aim of this study was to set-up and investigate the feasibility of on-farm composting techniques and compost application, starting from a case study in a Mediterranean experimental field. In particular, composting by using no-marketable products and vegetable biomass from crop residues as raw materials on-farm and analyzing the effect of the compost application in horticultural crops cultivation are the backbone of this study. Thus, the main objectives were (i) to evaluate the sustainability and the environmental impact of the "small scale" on-farm composting process trough EA and CF; (ii) to evaluate the agronomic performance and sustainability of the compost application compared to a conventional organic fertilizer in a two-year peppers-cover crops rotation; and (iii) to identify the management and environmental hotspots.

2. Materials and Methods

2.1. Study Site

The experimental activities, which include the on-farm composting process and the peppers–cover crops cultivation during the 2017–2018 to 2018–2019 period, were conducted in the experimental farm "Campo 7" of the Italian Council for Agricultural Research and Economics (CREA)— Research Centre for Agriculture and Environment at Metaponto, in Southern Italy (lat. 40°24′ N; long. 16°48′ E, 8 m above sea level). The area is characterized by mean monthly temperatures of 8.8 °C in the winter and 24.4 °C in the summer. The long-term annual average rainfall is about 500 mm year^{-1}, mainly concentrated in the winter months and the climate is classified as "accentuated thermomediterranean" by UNESCO-FAO [13]. The soil of the experimental farm is classified as Typic Epiaquerts [14], with clay content of about 60% and 30% silt. The N content is low, being 1.0 g kg^{-1}, and the average organic matter content is 19.0 g kg^{-1}. The pH value is 8.4, the electrical conductivity 0.48 mS cm^{-1} (1:10 (w/v) water-soluble extraction) and the average bulk density is 1350 kg m^{-3}.

2.2. Composting Plant Setup and Measurements

With the aim to recycle the agricultural waste materials produced in the experimental fields and to transfer the on-farm composting technology and know-how to the stakeholders, a small-scale composting plant was setup at the experimental farm. The composting plant is laid out on a concrete platform (100 m^2), to avoid the loss of percolates, in which a static windrow with active aeration is used as a composting method. The aeration system consists of a 0.55 kW power, an electrical panel equipped with a timer and a 90 PE pipe for a 3-meter length perforated at regular distances to ensure the correct aeration of the biomass above the pipe. The working capacity is about 1–2 m^3, allowing the farm to produce about 0.5–1.5 m^3 of finished product per each composting cycle, depending on the raw materials characteristics and amount.

The first step of the composting process was the pile preparation through shredding and mixing the raw materials. Once prepared, the composting pile was covered by a non-woven sheet to protect the materials from solar radiation and rain, without inhibiting gas exchanges. The proper oxygenation during the composting process was ensured by the aeration system activated regularly (ten minutes every two hours in the first two weeks). The pile temperature was measured continuously with two probes, positioned in two different points of the pile, connected to a data logger, while the composting pile moisture was regularly checked (weekly) and kept between 40 and 70%. To allow for homogenization and correct degradation in all biomasses, the pile was manually turned in a first stage (two times per week in the first two weeks, and once per week until the end of the process). At the end of the composting process, the compost was not sieved since this operation was not necessary. In fact, the raw materials used in the mixture were highly and easily degradable and quite small-sized.

All the waste materials were generated in the experimental farm and were firstly analyzed. The main characteristics of these organic materials are reported in Table 1. The chemical–physical characteristics of the raw materials and the obtained compost were determined according to a procedure reported in Ameen et al. and Yeomans and Bremner [15,16].

Table 1. Fresh weight, dry matter, pH, electrical conductivity (EC), total nitrogen (N) content and total organic carbon (TOC) of the raw materials used for the composting process.

Raw Materials	Fresh Weight (kg)	Dry Matter (%)	pH	EC (Meq 100 g^{-1})	N (%)	TOC (%)
Vicia faba minor L.	26.50	91.22 ± 0.78	7.37 ± 0.08	8.26 ± 0.17	1.34 ± 0.11	28.46 ± 13.94
Cucurbita pepo L. (plants and fruits)	75.00	61.02 ± 21.15	6.38 ± 0.87	18.15 ± 5.89	3.28 ± 0.04	25.91 ± 5.16
Festuca arundinacea Schreb/*Trifolium repens* L. 50/50%	79.50	87.86 ± 5.34	6.49 ± 0.08	6.72 ± 0.31	1.43 ± 0.09	27.43 ± 1.86
Festuca arundinacea Schreb/*Trifolium repens* L. 70/30%	165.30	89.00 ± 0.55	7.36 ± 0.03	6.42 ± 0.13	2.10 ± 0.67	30.65 ± 1.78
Compost (as starter)	4.00	76.20 ± 1.64	8.09 ± 0.06	9.65 ± 0.21	2.43 ± 0.20	18.81 ± 0.91

2.3. Experimental Design, Treatments and Crop Measurements

The experimental design of the two-year field trial was a split-plot with two factors and three replicates. The first plot factor consists of the introduction of the cover crops flattened with an in-line roller crimper (RC), while the second factor was assigned to fertilizers (F). The following three different treatments were defined by the first factor:

RC: A mix of vetch-oats (80% *Vicia sativa* L., 20% *Avena sativa* L., on seed weight base) during the autumn–winter period followed by peppers (*Capsicum annuum* L. var. Senise) during the spring–summer period, for the first-year cultivation, no cover crops during the second-year cultivation (due to adverse climatic conditions) and peppers in the spring–summer.

RC2: A mix of vetch-rice (80% *Vicia sativa* L., 20% *Oryza sativa* L., on seed weight base) during the autumn–winter period followed by peppers during the spring–summer period, no cover crops during the second-year cultivation (due to adverse climatic conditions) and peppers in the spring–summer.

CT: Two years of pepper cultivation without cover crops in both years.

The following three different fertilizing treatments were tested for the second factor:

ORG: An organic commercial fertilizer, based on dried animal manure used as a "positive" control.

OFC: The on-farm compost obtained by composting the experimental farm residues.

UF: An unfertilized "negative" control.

All the used fertilizers are allowed in organic farming, in accordance with the European Regulation (Commission Regulation N 889/2008 of 5 September 2008 for EU Council Regulation N 834/2007). The fertilizer rate (140 kg of N ha^{-1} for the peppers) was decided following local, national and European community rules and were applied one week before peppers transplanting. The phytosanitary management of pests and pathogens were the same in all plots and were in accordance with the Italian regulation for the organic production systems. Additionally, the irrigation management was the same in all analyzed theses and a drip irrigation system was utilized. The amount of water corresponded to 4600 m^3 ha^{-1} as an average of the two-year pepper cultivation. The mixtures of cover crops were sown in the autumn of 2017 and terminated, with the in-line roller crimper [17], on 19 April 2018. The peppers were manually transplanted (30,000 plants ha^{-1}, 0.4 m $\times$ 0.8 m) on 4 May 2018 and were harvested at commercial maturity from the last week of July 2018 to the beginning of September 2018. During the second year of cultivation, due to the adverse climatic conditions in the autumn/winter of 2018, the mixtures of cover crops were not sown. The peppers were transplanted on 3 May 2019 using the same amounts of plants as for the first-year cultivation. The fruits were harvested at a commercial maturity stage, which was reached from the beginning of August 2019 to the beginning of September 2019. Both years, during the pepper harvesting, the marketable yields (Mg ha^{-1}) were determined by recording the fresh and dry weights from three randomly selected plants in each plot. The aboveground plant biomass and the cover and weeds biomass were also determined as fresh and dry weights. The dry weights of the crop yields, and the above-ground biomasses of the crop residues, cover crops and weeds, expressed as Mg ha^{-1}, were obtained by drying in an oven at 72 °C for 48 h.

2.4. Sustainability Assessment

To evaluate the environmental sustainability of both the on-farm composting processes and the different management agricultural practices tested in the two-years pepper cultivation, EA and CF methods were applied, following the procedures reported by Pratibha et al. [18] and Persiani et al. [19]. The energy input and output and the carbon footprint (the amount of carbon dioxide emitted directly or indirectly) were estimated by means of several parameters measured and recorded directly in the experimental farm. These parameters include the human labor time, machineries weight and utilization time, irrigation equipment weights, water consumptions, fuels consumptions, fertilizers, seeds and plants, pesticides and yields. Total energy input and output as well as the GHG emissions and the C stocks, for the functional unit used (area, ha), were obtained by multiplying each input by its coefficient derived from the literature (Table 2).

Table 2. Energy equivalents and greenhouse gases coefficients (GHG) of each input and output for energy equivalents and of C emissions and C stocks for GHG coefficients, in crop production.

Inputs/C Emissions	Unit	Energy Equivalent (MJ unit^{-1})	References	Unit	GHG Coefficient (kg CO_2 eq./unit)	References
Human labor	h	1.96	[20]	h	0.36	[21]
Machinery	kg	62.7	[22]	MJ	0.071	[23]
Fuels						
Diesel	L	56.31	[20]	L	2.76	[23]
Electricity					0.608	[24]
Fertilizers						
Commercial organic fertilizer/compost	kg	0.73	[25]	kg	0.14	[25]
Comm.org. fert./compost direct emissions	kg			kg	0.057	[26]
Chemicals						
Insecticides	kg	199	[27]	kg	5.1	[28]
Fungicides	kg	92	[27]	kg	3.9	[29]
Irrigation water	m^3	1.02	[12]	m^3	0.27	[21]
Plastic pipes for irrigation	kg	120	[30]	kg	2.2	[31]
Seeds	kg	14.7	[32]			
Plantlets	n	0.2	[33]			
Emission factor (EF)				kg N_2O-N kg^{-1} N	0.005	[34]
Leaching factor of N ($FRAC_{Leach}$)				%	0.24	[34]
Volatilization of NH_3 and NO_x ($FRAC_{gas}$)				%	0.21	[34]
Leaching emission factor (EF_{Leach})				kg N_2O-N kg^{-1}	0.011	[34]
Volatilization emission factor (EF_{volat})				kg N_2O-N kg^{-1} N	0.005	[34]
Outputs/C stocks						
Peppers	kg	0.92	[35]	kg C kg^{-1} d.m.	0.55	
Plant residue and biomass	kg	0.3	[36]	kg C kg^{-1} d.m.	0.5–0.51	

The energy input and the GHG emissions were divided into categories (human labor, machinery, fuels, fertilizer, etc.). The energy was also divided into renewable and non-renewable categories according to Khojastehpour et al. [37]. Moreover, energy use efficiency and net energy were calculated, considering a whole system evaluation, by using the following formulas [38]:

$$\text{Net energy} = \text{energy output MJ ha}^{-1} \text{—energy input MJ ha}^{-1} \quad (1)$$

$$\text{Energy efficiency} = \text{energy output MJ ha}^{-1} / \text{energy input MJ ha}^{-1} \quad (2)$$

With regards to the GHG emissions, the further direct GHG impacts derived from the composting processes' direct emissions (Table 2), fertilizers and crops biomass decomposition generating N_2O emissions (leaching and volatilization) were accounted for. Consequently, the N_2O emissions were estimated following the procedure of IPCC [34], by using the coefficients reported in Table 2 and transformed into CO_2 equivalent (equivalent factors of 1 and 298 for CO_2 and N_2O, respectively). Finally, all the CO_2 generated during the processes was converted into C equivalents using the stoichiometric coefficient. The C stocked or lost due to the soil organic matter changes are not included in the study, although this may be an interesting point, because a two-year rotation is too short a time for accurately detecting changes in the soil organic matter. The C stocked in the biomasses (crop products, crop residues, covers and weeds) was calculated using the following formula reported in [19]:

$$C = B \times DM \times TOC \quad (3)$$

where C is C stocked in the biomass (kg ha^{-1}), B is the biomass value (kg ha^{-1}), DM is the dry matter content (%) and TOC is the total organic C (%, measured using the dry combustion method).

Thus, the system carbon difference (SCD), as the difference between C stocks and C emissions (i.e., C footprint), and the carbon efficiency of the different analyzed systems were calculated as follows:

$$SCD = C\ stocks - C\ emissions \quad (4)$$

$$\text{C efficiency} = \text{C stocks}/\text{C emissions} \quad (5)$$

where C stocks is the sum of the C stocked in the products and the C stocked in the biomasses; C emissions is the sum of the C eq. emissions generated during the field operations with the C eq. emissions (direct and indirect) estimated for the fertilizers and biomasses application into the soil.

2.5. Statistical Analysis

The analysis of variance (ANOVA) was carried out considering the cover management strategies, the fertilizer and the year as variability factors. To compare the differences obtained, means were analyzed using the Duncan test (at $p \leq 0.05$). Statistical analysis was carried out by using SPSS for Windows, Version 16.0. Since the ANOVA of the full analysis of variance, which involved the interactions between the three factors, was significant ($p > 0.05$) for most of the parameters analyzed (Table 3), the data were presented following the difference between all the combinations among the variability factors.

Table 3. Analysis of variance (ANOVA) of the different analyzed parameters (marketable yield, yield dry matter—d.m., fruit weight and plant biomass dry matter).

	Marketable Yield	Yield D.M.	Plant Biomass D.M.	Fruit Weight
Cover	***	***	**	*
Fert	**	**	*	**
Year	n.s.	n.s.	*	n.s.
Cover × Fert	**	**	***	*
Cover × Year	*	**	**	n.s.
Fert × Year	n.s.	*	***	n.s.
Cover × Fert × Year	n.s.	n.s.	**	n.s.

n.s., not significant. *, **, *** significant at p < 0.05, 0.01 and 0.001, respectively. Probability levels are presented for Cover, Fertilizer (Fert), Year and their interactions.

3. Results

3.1. Composting Process

Temperature profile monitored during the composting process is presented in Figure 1. Three main stages of composting (thermophilic, mesophilic and curing stages) can be clearly identified, according to the microorganisms' activity.

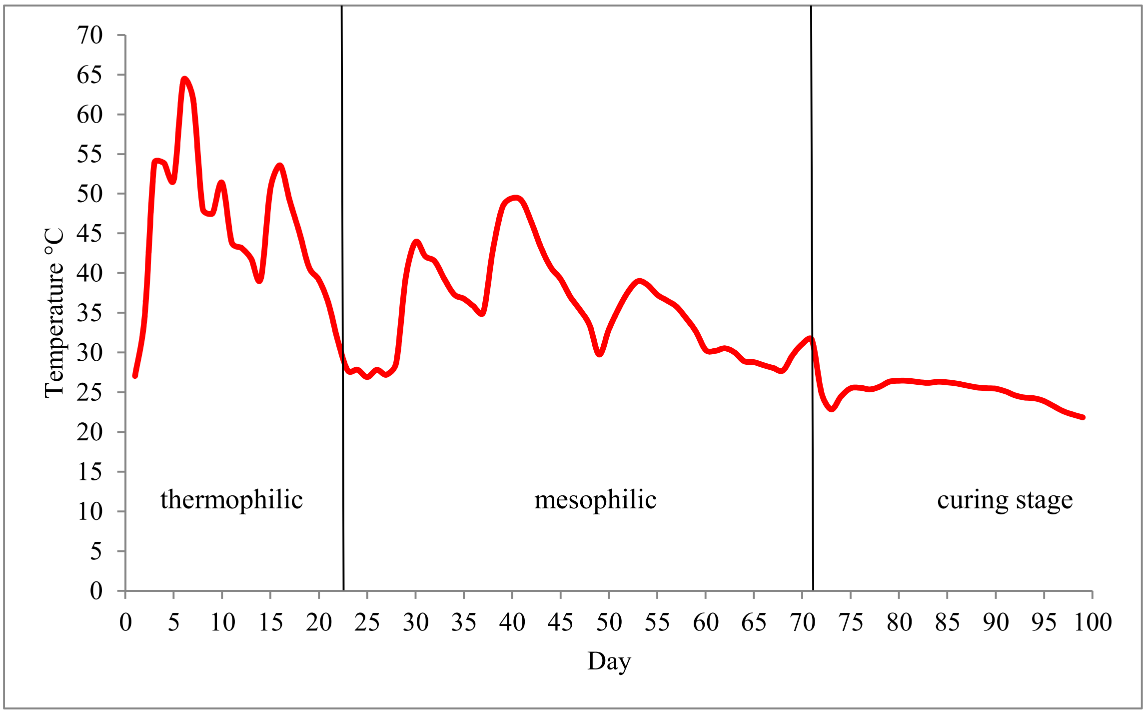

Figure 1. Temperature profile and main phases (thermophilic, mesophilic and curing stages) during the composting process.

A thermophilic phase was recorded in the first 16 days and reached the highest temperatures pick of 64 °C. The high temperatures recorded during this phase (53–64 °C) lasted long enough to guarantee the compost sanitization. After 20 days, the temperature started to decrease, allowing the mesophilic (35–50 °C) microorganisms to further carry out the decomposition of organic matter. After 65 days, the temperature decreased further and reached an ambient temperature (about 25 °C), thus indicating the end of the process and the curing phase by fungi.

Table 4 shows the evolution of the main physical–chemical characteristics of the organic materials during the degradation process. During composting, the water content was kept between 40 and 50% constantly by irrigation. The pH increased during the thermophilic phase and reached a maximum value of 8.23 at day 21, while it recorded a value 7.98 at the end of the process (typical value: 6–8). The EC values and the N content increased progressively reaching a final value of 11.91 ± 0.07 (meq 100 g^{-1}) and 2.79 ± 0.10 (%) for EC and N, respectively. The total C diminished constantly during the process and registered a final value of 22.02%, determining a decrease in the C/N ratio until it reached 7.9.

3.2. Agronomic Performances

The output of the analysis of variance revealed significant main effects of "Cover" (Table 3), on peppers' marketable yield, yield and plant biomass dry matters and fruit weights with $p < 0.001$, $p < 0.001$, $p > 0.01$ and $p > 0.05$ respectively. Additionally, "Fert" showed a significant main effect on the marketable yield and yield dry matters ($p > 0.01$), fruit weight ($p > 0.01$) and plant biomass dry matter ($p > 0.05$), while "Year" revealed a significant main effect only on plant biomass dry matter ($p > 0.05$). A significant interaction between Cover x Fert and Cover x Year was also found for all the parameters except fruit weight, whereas the interaction Fert x Year was positive for plant biomass dry matter ($p > 0.001$) and yield dry matter ($p > 0.05$). No statistically detectable interaction was found for Cover x Fert x Year except for plant biomass ($p > 0.05$).

Table 4. Chemical parameters change during composting process (day 1 to 90): dry matter, pH, electrical conductivity (EC) (1/5 mL H_2O), total nitrogen (N) content, total organic carbon (TOC) and C/N ratio.

Day of the Composting Process	Dry Matter(%)	pH	EC (Meq 100 g^{-1})	N (%)	C (%)	C/N
1	48.84 ± 16.16	7.82 ± 0.30	8.23 ± 1.70	2.43 ± 0.05	28.31 ± 4.56	11.67
8	61.41 ± 1.81	8.11 ± 0.08	9.60 ± 0.26	2.38 ± 0.04	26.33 ± 1.15	11.09
21	51.71 ± 4.58	8.23 ± 0.06	9.53 ± 0.19	2.54 ± 0.02	25.94 ± 1.02	10.22
42	51.73 ± 3.69	7.92 ± 0.10	9.23 ± 1.23	2.80 ± 0.16	22.98 ± 1.52	8.20
70	46.67 ± 4.07	7.87 ± 0.06	11.07 ± 0.56	2.72 ± 0.07	23.09 ± 0.78	8.48
90	60.26 ± 1.90	7.98 ± 0.05	11.91 ± 0.07	2.79 ± 0.10	22.02 ± 0.45	7.90

The treatment effects on peppers in each cropping season are reported in Table 5. In 2018, the highest value of marketable yield was found in RC2-OFC and RC2-ORG, whereas the CT-UF treatment showed the lowest one (not statistically different from CT-OFC), with a 98% reduction compared to RC2-OFC. During the second-year cultivation, the trend was similar among a combination of treatments, except for the RC2-OFC treatment that showed a value statistically comparable with CT-ORG and RC2-ORG. The yield dry matter and the plant biomass were proportional to the marketable yields being higher in RC2-OFC and RC2-ORG in both years, and lower in the CT-UF treatment in 2018 and CT-OFC in 2019. The fruit weight values were statistically comparable in all the treatments, except the CT-UF in 2018 and CT-OFC in 2019 that showed lower absolute values, being −38 and −21%, respectively, compared to the overall average.

Table 5. Marketable yield fresh weight and yield dry matter, fruit weight and plant biomass dry matter in the two-year pepper cultivation.

Year	Cover	Fert	Marketable Yield (Mg ha^{-1})		Yield D.M. (Mg ha^{-1})		Fruit Weight (g)		Plant Biomass D.M. (Mg ha^{-1})	
1	RC	ORG	2.73	cde	0.38	c	18.45	a	0.17	ef
1	RC	OFC	4.31	cde	0.69	c	16.12	ab	0.42	cdef
1	RC	UF	1.73	cde	0.25	c	18.03	a	0.17	ef
1	RC2	ORG	9.43	ab	1.39	ab	18.77	a	0.83	ab
1	RC2	OFC	11.95	a	1.84	a	19.65	a	1.13	a
1	RC2	UF	1.20	cde	0.17	c	16.58	ab	0.15	ef
1	CT	ORG	2.72	cde	0.45	c	19.22	a	0.69	bcd
1	CT	OFC	1.06	de	0.17	c	13.26	abc	0.18	ef
1	CT	UF	0.28	de	0.06	c	6.67	c	0.06	e
2	RC	ORG	3.72	cde	0.53	c	19.35	a	0.24	ef
2	RC	OFC	4.13	cde	0.60	c	15.75	ab	0.27	ef
2	RC	UF	3.91	cde	0.54	c	18.47	a	0.33	def
2	RC2	ORG	6.08	bcd	0.74	bc	17.63	ab	0.46	cde
2	RC2	OFC	6.33	bc	0.74	bc	17.54	ab	0.40	cdef
2	RC2	UF	1.52	cde	0.23	c	13.36	abc	0.14	ef
2	CT	ORG	6.07	bcd	0.72	bc	20.72	a	0.09	ef
2	CT	OFC	0.83	de	0.12	c	10.02	bc	0.15	ef
2	CT	UF	3.35	cde	0.51	c	12.91	abc	0.71	bc

Notes: (1 = 2018; 2 = 2019; RC = mix of vetch-oats; RC2 = mix of vetch-rice; CT = no cover crops; ORG = organic commercial fertilizer; OFC = on-farm compost; UF = unfertilized control). Mean values, in columns, followed by the same letter are not significantly different according to a Duncan test (p = 0.05).

3.3. Environmental Sustainability Assessment

The analyses of the energetic consumption and the emissions of carbon dioxide during the on-farm composting process showed that the production of 1 Mg of on-farm compost required a total of 319 MJ (Figure 2).

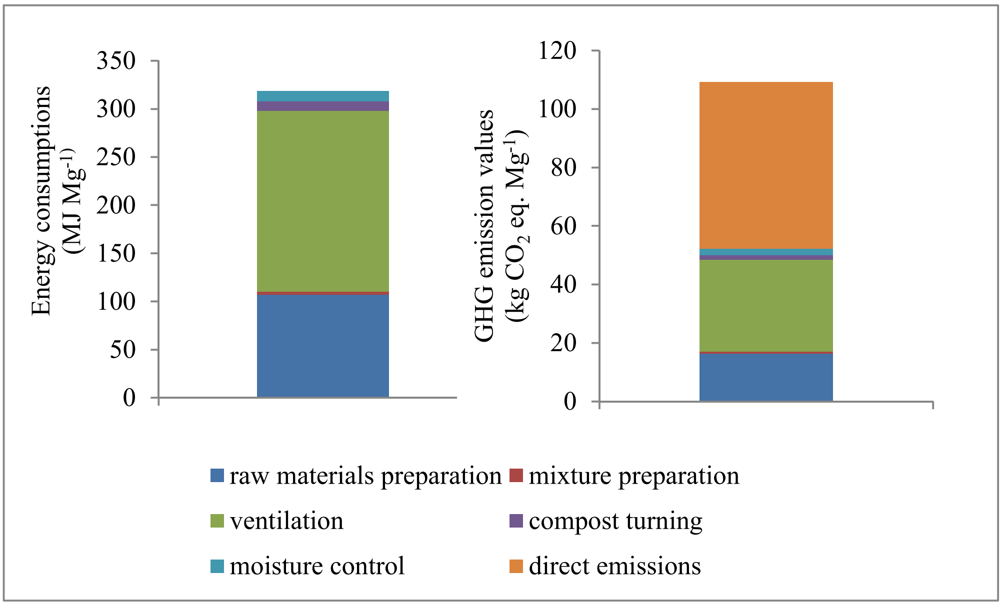

Figure 2. Energy used (MJ Mg^{-1} compost produced) and GHG emission values (kg CO_2 eq. Mg^{-1} compost produced) for the composting process divided by each treatment operation.

The results illustrate that the main factors contributing to the energetic consumptions were the ventilation, representing 58.9% of the total energy consumption, and the energy use for materials preparation, which was 33.6% of the total emissions. The carbon dioxide emissions during the process were estimated as having a total of 109.16 kg CO_2 eq. Mg^{-1} of compost produced. The main factors that contributed to these emissions were the direct emissions (52.2%) generated during the process, followed by the emissions related to the energy consumed due to the ventilation (28.2%) and the preparation of the raw materials (15%).

In Figure 3, the two-year average energetic consumption related to the cultivation processes and divided by productions factors, energetic outputs and net energy are reported. The EA revealed that RC2-ORG, RC-ORG and CT-ORG combined treatments consumed a greater total energy input ha^{-1} $year^{-1}$ than the other systems. The analysis of the inputs by production factors indicated that the fertilizer was the factor that caused the greater dissimilarity between the systems, being, on average 23.2, 11.8 and 0% of the total energy inputs in the ORG, OFC and UF treatments, respectively. The other input categories that required huge amounts of energy were water (25.4%), seeds and plants (24.2%), fuels (19.4%) and irrigation equipment (12.6%).

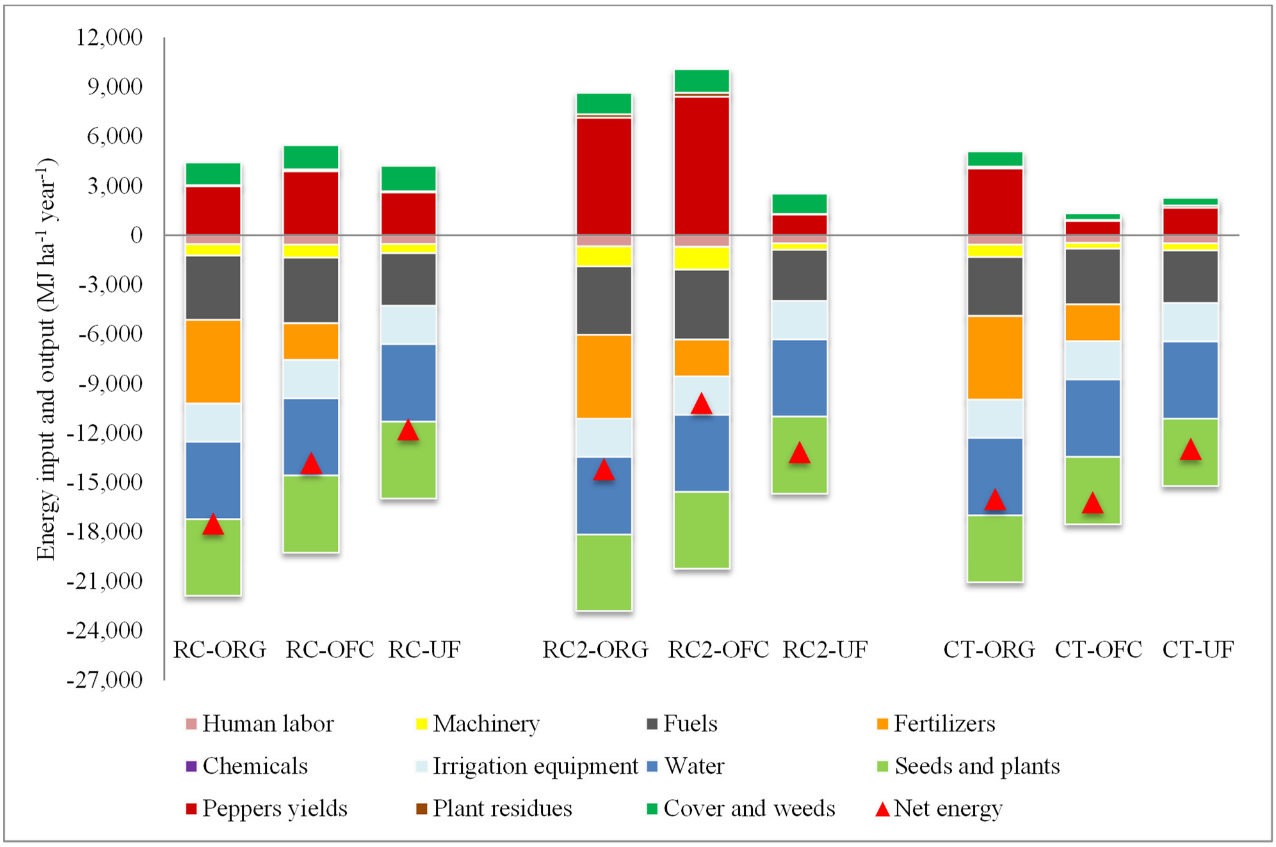

Figure 3. Energetic consumptions (inputs), energy gain (output) and net energy expressed as MJ ha^{-1} year^{-1} in the different analyzed systems. RC = mix of vetch-oats; RC2 = mix of vetch-rice; CT = no cover crops; ORG = organic commercial fertilizer; OFC = on-farm compost; UF = unfertilized control.

The total energy output was strictly related to the production, showing a value of 10084 MJ ha^{-1} year^{-1} in the RC2-OFC, followed by RC2-ORG (−14.3% compared to RC2-OFC) and RC-OFC (−45.9% compared to RC2-OFC), while the lowest values were found in CT-OFC (1328 MJ ha^{-1} year^{-1}), CT-UF (2277 MJ ha^{-1} year^{-1}) and RC2-UF (2523 MJ ha^{-1} year^{-1}).

All the analyzed treatments registered negative net energy values and the RC2-OFC showed the best result (−10170 MJ ha^{-1} year^{-1}), while the lowest value was observed in RC-ORG (−17480 MJ ha^{-1} year^{-1}). In all the systems, higher amounts of renewable than no renewable energy were consumed on average, being 64.3 and 35.7 %, respectively (Figure 4), while irrelevant differences were observed among the cover and fertilizers' variability factors. The RC2-OFC system was the most energy efficient (0.50), followed by RC2- ORG (0.38) and RC-OFC (0.28).

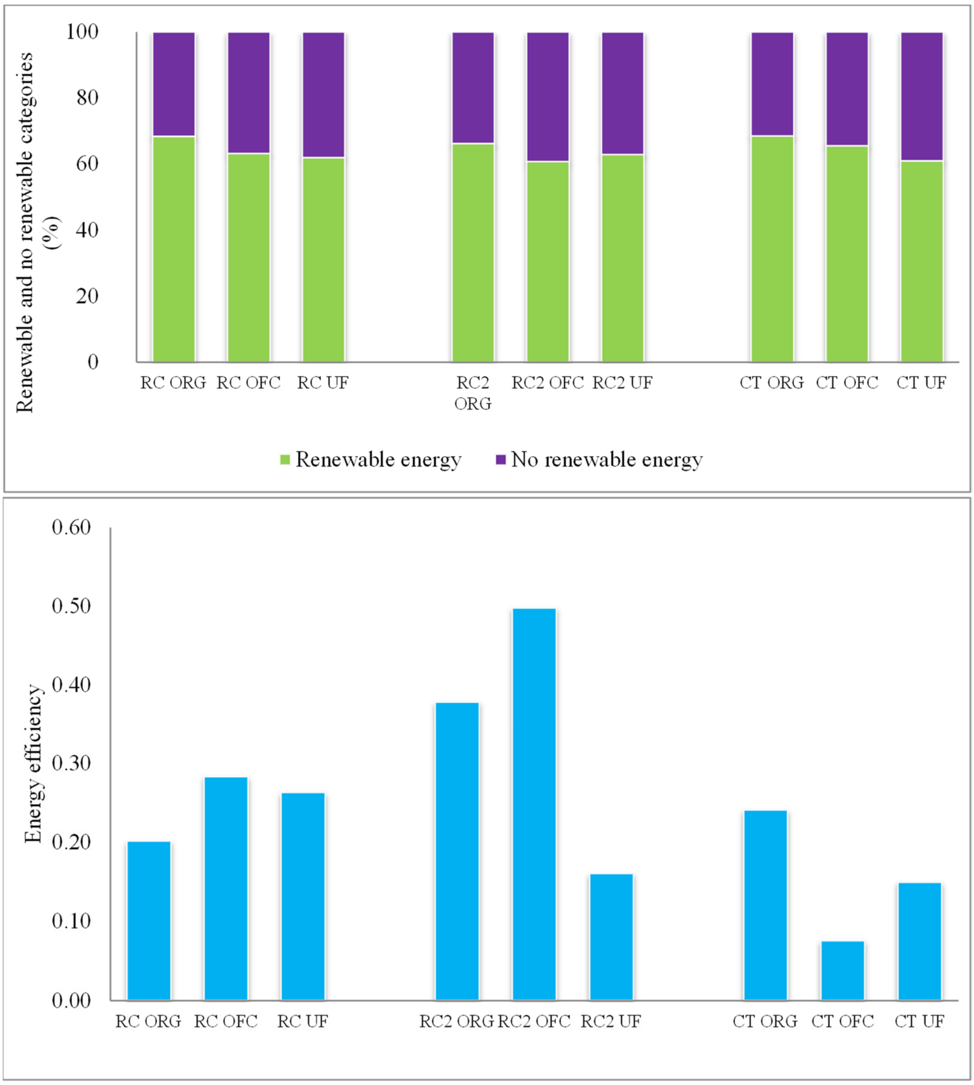

Figure 4. Energy efficiency and energy input divided by renewable and no renewable categories (%) in the different analyzed systems. RC = mix of vetch-oats; RC2 = mix of vetch-rice; CT = no cover crops; ORG = organic commercial fertilizer; OFC = on-farm compost; UF = unfertilized control.

Figure 5 shows that the carbon loss, derived by the sum of the CO_2 emitted in the cultivation processes and the CO_2 eq. generated by the N_2O emissions, was, on average, higher in the RC and RC2 treatments than in UF (−10.4% compared to the average of RC and RC2), and in ORG compared to OFC (−6% compared to ORG) and UF treatments (−46% compared to ORG). The total C stocks, which is the sum of the C stocked in the products with C in the plant residues and in the cover and weeds, were higher in RC2-OFC, with a value of 3570.9 kg C ha^{-1} $year^{-1}$, RC-OFC and RC2-ORG (−6.7 and −11.9% compared to RC2-OFC, respectively), whereas a very low value was shown by CT-OFC and CT-UF (−76 and −75% compared to RC2-OFC, respectively).

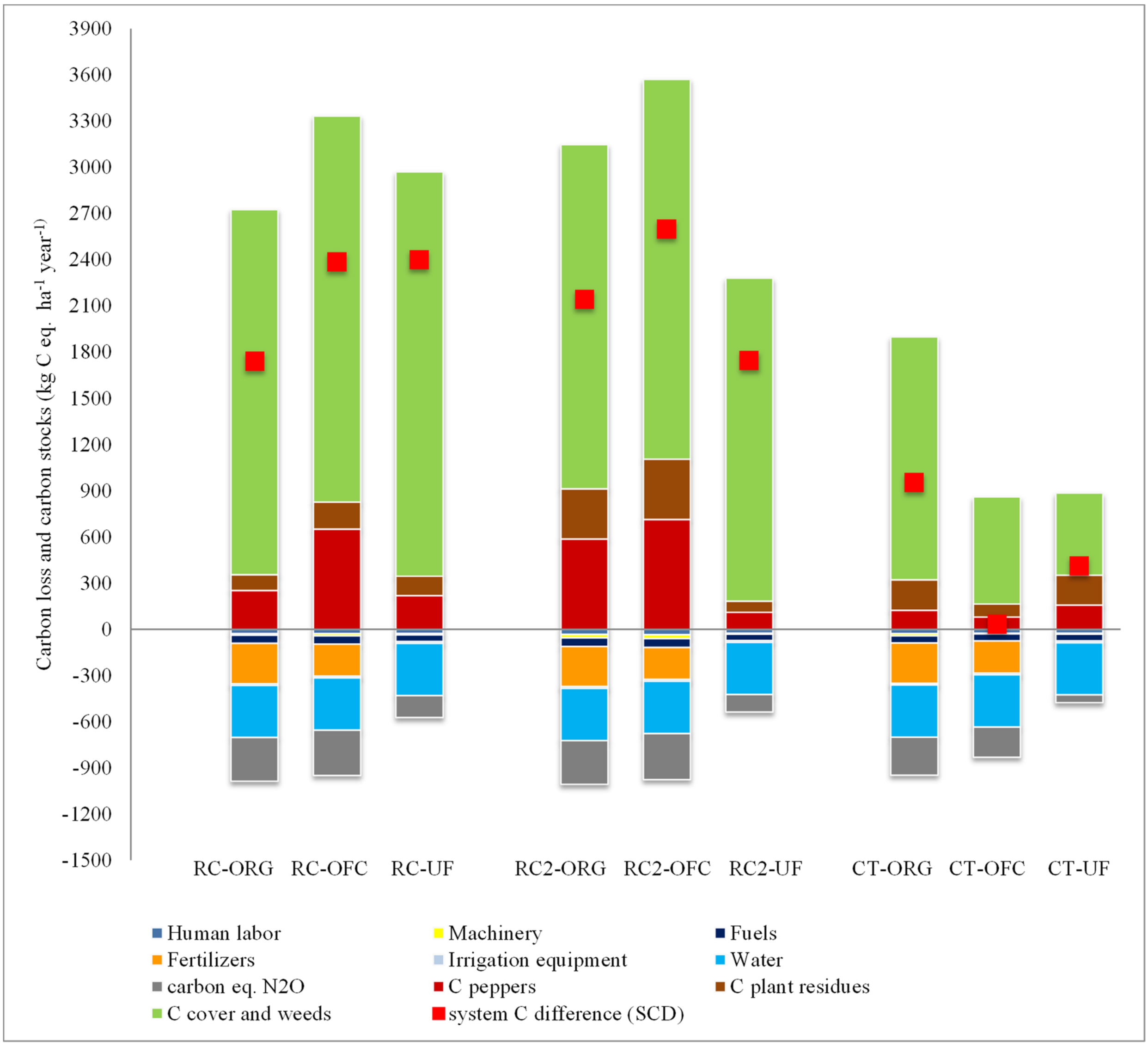

Figure 5. Carbon loss (emissions), carbon stocks and system carbon difference (SCD) expressed as Kg C eq. ha^{-1} year^{-1} in the different analyzed systems. RC = mix of vetch-oats; RC2 = mix of vetch-rice; CT = no cover crops; ORG = organic commercial fertilizer; OFC = on-farm compost; UF = unfertilized control.

The difference between C stocks and C emissions (SCD) was the highest for RC2-OFC (2596.24 kg C ha^{-1} year^{-1}), followed by RC-C (2397.64 kg C ha^{-1} year^{-1}) and RC-OFC (2384.51 kg C ha^{-1} year^{-1}). CT-OFC, CT-UF and CT-ORG showed the lowest values being 31.21, 409.23 and 952.53 kg C ha^{-1} year^{-1}, respectively. The carbon efficiency for each system, as reported in Figure 6, registered higher value in RC-C followed by RC2-UF and RC2-OFC, being 5.19, 4.24 and 3.66, respectively.

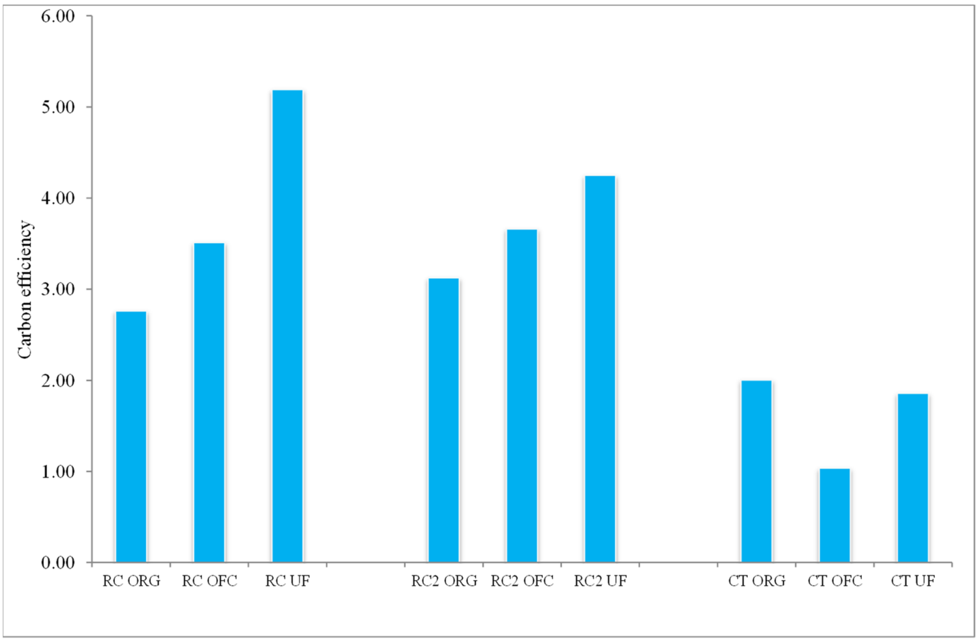

Figure 6. Carbon efficiency in the different analyzed systems. RC = mix of vetch-oats; RC2 = mix of vetch-rice; CT = no cover crops; ORG = organic commercial fertilizer; OFC = on-farm compost; UF = unfertilized control.

4. Discussion

4.1. Composting Process

Temperature is an essential affecting factor for microorganisms' activity in the composting process and is critical for dominant bacterial strains to be efficient. As also observed in many studies [39,40], in our on-farm composting, the temperature increased rapidly at the beginning of the process, which indicates good biodegradation conditions and the rapid establishment of microbial populations in the composting pile. Moreover, the recorded high temperature picks and the sufficient duration of the thermophilic phase are considered optimal conditions to provide the compost sanitization [41]. Then, the temperature decrease indicated that most of the complex organic compounds were degraded during the thermophilic and mesophilic stages.

According to Liu et al. [39], the value of pH of the composting pile was in the optimal range (7.0–8.0) to stimulate the microbial activities. The pH value raised during the thermophilic phase, while a reduction and stabilization of pH was observed at the end of the process. As reported in Echevarria et al. [41], the initial increase in pH was probably due to the degradation of acidic compounds and the emission of ammonia as a consequence of proteins mineralization while, as organic compounds were decomposed, organic acids were generated under the action of microbes, which caused the slow drop of the compost pH and then its stabilization [42]. In line with the findings reported by Ameen et al. [15], the EC increased during the composting and the value was resultingly higher at the end of the process.

The C/N ratio is the widest used index of the compost stability and maturity because it is more sensitive to chemical changes of the organic matter than either N or C contents alone. In this study, the initial value of C/N ratio in the mixture was lower than the optimal values (20–30) [43], due to the nature of the raw materials available in the farm for composting. However, the C/N ratio at the end of the process showed a 32% decrease and this value reveals both the aerobic decomposition of organic matter, due to biodegradation and its stabilization during composting.

4.2. Agronomic Performances

The marketable yield values pointed out that, in agreement with other studies [44,45], the introduction of the cover crops in the horticultural rotation, terminated by the no-till technique, may positively affect the cash crop productions. Conversely, other studies report that the conservation techniques may generate, particularly in the short periods, yield reduction due to temporary N immobilization phenomena and competition between cover crops and cash crops [46,47]. The differences between treatments with cover crops and CT were likely due to the higher N input to soil derived by the decomposition of the cover crops that, in our experiment, was accentuated by the inclusion of a legume crop in the mix [48].

As regards the fertilization variability factor, on the whole, the ORG and the OFC treatments showed higher productions than the UF treatments (−62%, on average, compared to the fertilized treatments), confirming that fertilization is an essential production factor in horticultural crop cultivation [49]. However, in systems without cover crops (CT), the differences between the fertilized and unfertilized treatments were lower, confirming the strong and positive interaction between RC and fertilizers and particularly between RC and OFC. Not statistically relevant differences were found between the commercial organic fertilizer (ORG) and the on-farm compost (OFC). This result, in agreement with many other studies [3,50,51], confirmed the feasibility and the quality of the compost produced directly on-farm to support plant nutrition and sustain the agricultural productions.

4.3. Environmental Sustainability Assessment

In our experimental conditions, the production of 1 Mg of on-farm compost needed 319 MJ of energy and this value was in line with the findings (297 MJ Mg-1) of Blengini et al. [52] and other studies on low technology composting based on turned windrows [4,53,54]. Conversely, less energy than more complex industrial composting plants was required in our process [25]. The largest part of energetic consumption was generated by the ventilation process (58.8%) and raw materials preparation due to the electric shredder (33.6%). As observed in the EA, the analysis of the CO_2 emissions revealed that the total emissions generated by the on-farm composting were lower than those reported by more complex industrial composting technologies [53,55] and were comparable with the low technology/on-farm composting values reported [22,30,32] by Pergola et al. [54], Pampuro et al. [56] and Colon et al. [57]. Moreover, in our study, the CO_2 fluxes that include the avoided emissions that would have occurred under green waste management, as well as the enhanced C sequestration from land application of compost, as described in other studies [26,58], were not evaluated. Considering a system boundary that includes these avoided emissions (landfill for green waste and enhanced C sequestration potential), they would have outweighed the sum of the direct and indirect emissions generated during the on-farm composting.

The EA over the whole crop cycle reveals that the introduction of the cover crops associated with the no-till termination (RC systems) generated small energetic consumption differences, compared to CT. As observed by Navarro-Mirò et al. [59] (2019) and Diacono et al. [60], the slightly higher energetic input requirements in RC were due to farming operations related to the cover crop, in particular the cover crop sowing and termination, which generated human labor, machinery and fuels consumptions. Conversely, the different fertilization strategy generated huge variations among the systems confirming that this operation is crucial for the whole system sustainability [59,61]. In fact, in this study, the ORG treatment showed the highest energetic consumption followed by OFC (−13% compared to ORG) and unfertilized treatment (C) (−29% compared to ORG). Other small differences among the energy consumption were due to the harvest operation, which varied proportionally to the yields. Since energy output was directly proportional to the yield and biomass, the highest energy output was detected in the most productive treatments (RC2-OFC, RC2-ORG and RC-OFC). Small differences in the outputs were also detected in the treatments that registered the highest plant residues and cover crops/weeds biomass (RC systems).

All the systems had a negative "net energy" value, and the RC2-OFC showed the best results for this index. Good results were also found in the C treatment, because of the very low energy input requirements, although this treatment was not agronomically sustainable due to the very low outputs. RC2-OFC also showed the best energy efficiency followed by RC2-ORG and RC-OFC due to the high energy output related to the yields.

As observed for the EA, in the SCD, the treatment without fertilizers (UF) generated low carbon loss as compared to the OFC and ORG treatments. As found in other studies [18,61], UF avoided the CO_2 emissions due to the fertilizers production and further direct and indirect impacts derived from fertilizers decomposition, which generates N_2O emissions from soils, N leaching and volatilization phenomena [34]. These results were also in agreement with Zou et al. [62] and Jin et al. [63], who studied the direct measurements of the N_2O, NO, CH_4 fluxes and ecosystem respiration with consequent CO_2 eq. emissions. Therefore, although the direct measurements are the best way to evaluate these emissions in all crop production and environmental situations, even with different crops and environment our results seem quite comparable, estimating the direct and indirect emissions generated by fertilizers and crop biomasses added to the soil. Moreover, according to a study conducted by Hwang et al. [64], the N derived from the cover crop biomass generates consistent emissions that lead to differences between the systems, especially when leguminous crops are used. In our study, the emissions derived by the cover and biomass decomposition determined low differences among analyzed systems, and the treatment that included the cover crops (RC) showed slightly higher impact than CT. Conversely, the cover crops may mitigate the soil emissions due to the albedo change, which affects the net radiation [65]. However, due to the high variability of these effects that can lead to uncertainties in the values [65,66], and the small differences between the systems that are negligible for a very impacting system such as the horticultural one, in this study the albedo change effect linked to the cover introduction was not measured.

The analysis of the C stocks revealed high value in the systems that include the cover crops in association with high productions (RC2-OFC, RC-OFC and RC2-ORG). These systems also showed the highest difference between C stocks and C emissions (SCD) and confirmed the findings of Diacono et al. [45], who reported high sustainability associated with good production in the systems with cover crops in the rotation. The C efficiency reveals that the systems that included the cover (RC and RC2) without fertilizers (UF) were sustainable from an environmental point of view, due to the good C stocks generated by the cover crops biomass, associated with the very low negative impacts in terms of fertilization reduction and soil losses [67]. However, these treatments can be considered unsustainable from an agronomic point of view, due to very low production values.

5. Conclusions

Modern agricultural systems should combine high and healthy agricultural productions with environmental benefits and high efficiency, to make the agricultural systems more sustainable. This study confirmed the hypothesis that the on-farm composting of agricultural wastes is a viable option to meet the new needs of a circular economy, since this technique enhances the productivity and quality of crops while reducing the quantity of organic waste and the needs of external inputs (e.g., fertilizers and pesticides). The results revealed that producing good quality compost directly on-farm is feasible and more sustainable than using commercial organic fertilizer. The on-farm compost showed good results both in terms of production (statistically equal to ORG) and the environmental sustainability of the whole production cycle. The research results also pointed out a synergistic effect due to the combination of the compost in association with the cover crops terminated with the no-till roller crimper. In fact, the RC-OFC combination showed the best agronomic performance, being the most energetic efficient one and showed the highest difference between C stocks and C emissions. These results should encourage farmers to produce compost directly on their farms, to enhance the sustainability and reduce the need of more expensive commercial fertilizers allowed in organic production.

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References

1. De Corato, U. Agricultural waste recycling in horticultural intensive farming systems by on-farm composting and compost-based tea application improves soil quality and plant health: A review under the perspective of a circular economy. *Sci. Total Environ.* **2020**, *738*, 139840. [CrossRef]
2. Locatelli, B.; Pavageau, C.; Pramova, E.; Di Gregorio, M. Integrating climate change mitigation and adaptation in agriculture and forestry: Opportunities and trade-offs. *Wiley Interdiscip. Rev. Clim. Chang.* **2015**, *6*, 585–598. [CrossRef]
3. Diacono, M.; Persiani, A.; Testani, E.; Montemurro, F.; Ciaccia, C. Recycling agricultural wastes and by-products in organic farming: Biofertilizers production, yield performance and carbon footprint analysis. *Sustainability* **2019**, *11*, 3824. [CrossRef]
4. Persiani, A.; Pergola, M.; Ingrao, C.; Palese, A.M.; Celano, G. Supply of agricultural biomass residues for onfarm composting: A cross-analysis of relevant data sets for the most sustainable management combination. *Agroecol. Sustain. Food Syst.* **2021**, *45*, 134–156. [CrossRef]
5. Peigné, J.; Girardin, P. Environmental impacts of farm-scale composting practices. *Water Air Soil Pollut.* **2003**, *153*, 45–68. [CrossRef]
6. Aguilera, A.; Lassaletta, L.; Gattinger, A.; Gimeno, B.S. Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agric. Ecosyst. Environ.* **2013**, *168*, 25–36. [CrossRef]
7. Palese, A.M.; Persiani, A.; D'Adamo, C.; Pergola, M.; Pastore, V.; Sileo, R.; Ippolito, G.; Lombardi, M.A.; Giuseppe, G. Composting as manure disposal strategy in small/medium-size livestock farms: Some demonstrations with operative indications. *Sustainability* **2020**, *12*, 3315. [CrossRef]
8. Viaene, J.; Van Lancker, J.; Vandecasteele, B.; Willekens, K.; Bijttebier, J.; Ruyss-chaert, G.; De Neve, S.; Reubens, B. Opportunities and barriers to on-farm composting and compost application: A case study from north-western Europe. *Waste Manag.* **2016**, *48*, 181–192. [CrossRef] [PubMed]
9. Brown, S.; Kruger, C.; Subler, S. Greenhouse gas balance for composting operations. *J. Env. Qual.* **2008**, *37*, 1396–1410. [CrossRef] [PubMed]
10. Meul, M.; Nevens, F.; Reheul, D.; Hofman, G. Energy use efficiency of specialised dairy, arable and pig farms in Flanders. *Ecosyst. Environ.* **2007**, *119*, 135–144. [CrossRef]
11. Pérez Neira, D.; Soler Montiel, M.; Simón Fernández, A. Energy analysis of organic farming in Andalusia (Spain). *Agroecol. Sustain. Food Syst.* **2013**, *37*, 231–256.
12. Yousefi, M.; Khoramivafa, M.; Mahdavi Damghani, A. Water footprint and carbon footprint of the energy consumption in sunflower agroecosystems. *Environ. Sci. Pollut. Res.* **2017**, *24*, 19827–19834. [CrossRef]
13. UNESCO-FAO. *Bioclimatic Map of the Mediterranean Zone*; UNESCO-FAO: Paris, France, 1963; p. 60.
14. Soil Survey Staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*; Agriculture Handbook 436; USDA-NRCS: Washington, DC, USA, 1999.
15. Ameen, A.; Ahmad, J.; Munir, N.; Raza, S. Physical and chemical analysis of compost to check its maturity and stability. *Eur. J. Pharm. Med. Res.* **2016**, *3*, 84–87.
16. Yeomans, J.C.; Bremner, J.M. A rapid and precise method for routine determination of organic carbon in soil. *Commun. Soil Sci. Plant Anal.* **1988**, *19*, 1467–1476. [CrossRef]
17. Diacono, M.; Fiore, A.; Farina, R.; Canali, S.; Di Bene, C.; Testani, E.; Montemurro, F. Combined agro-ecological strategies for adaptation of organic horticultural systems to climate change in Mediterranean environment. *Ital. J. Agron.* **2016**, *11*, 85–91. [CrossRef]
18. Pratibha, G.; Srinivas, I.; Rao, K.V.; Raju, B.M.K.; Thyagaraj, C.R.; Korwar, G.R.; Venkateswarlu, B.; Arun Shanker, K.; Deepak Choudhary, K.; Srinivas Rao, K.; et al. Impact of conservation agriculture practices on energy use efficiency and global warming. *Eur. J. Agron.* **2015**, *66*, 30–40. [CrossRef]

19. Persiani, A.; Diacono, M.; Monteforte, A.; Montemurro, F. Agronomic performance, energy analysis and carbon balance comparing different fertilization strategies in horticulture under Mediterranean conditions. *Environ. Sci. Pollut. Res.* **2019**, *26*, 19250. [CrossRef]
20. Singh, R.S.; De, D.; Chandra, H. Energy efficiency for wheat production under irrigated condition in Madhya Pradesh. *J. Asian Econ. Rev.* **2001**, *43*, 236–244.
21. Ozalp, A.; Yilmaz, S.; Ertekin, C.; Yilmaz, I. Energy analysis and emissions of greenhouse gases of pomegranate production in Antalya Province of Turkey. *Erwerbs-Obstbau* **2018**, *60*, 321–329. [CrossRef]
22. Mittal, J.P.; Dhawan, K.C. *Research Manual on Energy Requirements in Agricultural Sector*; ICAR: New Delhi, India, 1988; pp. 20–23.
23. Dyer, J.A.; Desjardins, R.L. Simulated farm fieldwork, energy consumption and related greenhouse gas emissions in Canada. *Biosyst. Eng.* **2003**, *85*, 503–513. [CrossRef]
24. Khoshnevisan, B.; Rafiee, S.; Omid, M.; Yousefi, M.; Movahedi, M. Modeling of energy consumption and GHG (greenhouse gas) emissions in wheat production in Esfahan province of Iran using artificial neural networks. *Energy* **2013**, *52*, 333–338. [CrossRef]
25. Colón, J.; Cadena, E.; Pognani, M.; Barrena, R.; Sánchez, A.; Font, X. Determination of the energy and environmental burdens associated with the biological treatment of source-separated Municipal Solid Wastes. *Energy Environ. Sci.* **2012**, *5*, 5731. [CrossRef]
26. Vergara, S.E.; Silver, W.L. Greenhouse gas emissions from windrow composting of organic wastes: Patterns and emissions factors. *Environ. Res. Lett.* **2019**, *14*, 124027. [CrossRef]
27. Helsel, Z.R. Energy and alternatives for fertiliser and pesticide use. In *Energy in World Agriculture*; Fluck, R.C., Ed.; Elsevier: Amsterdam, The Netherlands, 1992; pp. 172–210.
28. Lal, R. Carbon emission from farm operations. *Environ. Int.* **2004**, *30*, 981–990. [CrossRef]
29. Graefe, S.; Tapasco, J.; Gonzalez, A. Resource use and greenhouse gas emissions of eight tropical fruits species cultivated in Colombia. *Fruits* **2013**, *68*, 303–314. [CrossRef]
30. Page, G. An Environmentally-Based Systems Approach to Sustainability Analysis of Organic Fruit Production Systems in New Zealand. Ph.D. Thesis, Massey University, Palmerston North, New Zealand, 2009. Available online: http://hdl.handle.net/10179/825 (accessed on 20 March 2021).
31. Martinez-Mate, M.A.; Martin-Gorriz, B.; Martínez-Alvarez, V.; Soto-García, M.; Maestre-Valero, J.F. Hydroponic system and desalinated seawater as an alternative farm productive proposal in water scarcity areas: Energy and greenhouse gas emissions analysis of lettuce production in southeast Spain. *J. Clean. Prod.* **2018**, *172*, 1298–1310. [CrossRef]
32. Baran, M.F.; Gokdogan, O. Energy input-output analysis of barley production in Thrace region of Turkey. *Am. J. Agric. Environ. Sci.* **2014**, *14*, 1255–1261.
33. Bojaca, C.R.; Schrevens, E. Energy assessment of peri-urban horticulture and its uncertainty: Case study for Bogota, Colombia. *Energy* **2010**, *35*, 2109–2118. [CrossRef]
34. Intergovernmental Panel on Climate Change (IPCC). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019; Volume 4.
35. USDA. United States Department of Agriculture Agricultural Research Service National Nutrient Database for Standard Reference Legacy Release. 2021. Available online: https://ndb.nal.usda.gov/ndb/ (accessed on 29 January 2021).
36. Spugnoli, P.; Baldi, F.; Parenti, A. L'analisi energetica per un miglior uso delle risorse nei processi agricoli. Applicazione ad aziende agricole toscane [Energy analysis for a better use of resources in agricultural processes. Application to Tuscan farms]. *Riv. Ing. Agrar.* **1993**, *24*, 225–233.
37. Khojastehpour, M.; Nikkhah, A.; Hashemabadi, D.A. Comparative study of energy use and greenhouse gas emissions of canola production. *Int. J. Agric. Manag.* **2015**, *5*, 51–58. [CrossRef]
38. Namdari, M.; Kangarshahi, A.A.; Amiri, N.A. Input-output energy analysis of citrus production in Mazandaran province of Iran. *Afr. J. Agric. Res.* **2011**, *6*, 2558–2564.
39. Liu, L.; Wang, S.; Guo, A.; Zhao, T.; Zhang, B. Succession and diversity of microorganisms and their association with physicochemical properties during green waste thermophilic composting. *Waste Manag.* **2018**, *73*, 101–112. [CrossRef]
40. Chaher, N.E.H.; Chakchouk, M.; Nassour, A.; Nelles, M.; Hamdi, M. Potential of windrow food and green waste composting in Tunisia. *Environ. Sci. Pollut. Res.* **2021**, *28*, 46540–46552. [CrossRef]
41. Echeverria, M.C.; Cardelli, R.; Bedini, S.; Colombini, A.; Incrocci, L.; Castagna, A.; Agnolucci, M.; Cristani, C.; Ranieri, A.; Saviozzi, A.; et al. Microbially-enhanced composting of wet olive husks. *Bioresour. Technol.* **2012**, *104*, 509–517. [CrossRef]
42. Sun, D.Q.; Lan, Y.; Xu, E.G.; Meng, J.; Chen, W.F. Biochar as a novel niche for culturing microbial communities in composting. *Waste Manag. (Oxf.)* **2016**, *54*, 93–100. [CrossRef] [PubMed]
43. Dell'Abate, M.T.; Benedetti, A.; Sequi, P. Thermal methods of organic matter maturation monitoring during a composting process. *J. Therm. Anal. Calorim.* **2000**, *61*, 389–396. [CrossRef]
44. Adekiyaa, A.O.; Agbedeb, T.M.; Aboyejia, C.M.; Dunsin, O. Response of okra (*Abelmoschus esculentus* (L.) Moench) and soil properties to different mulch materials in different cropping seasons. *Sci. Hortic.* **2017**, *217*, 209–216. [CrossRef]
45. Diacono, M.; Persiani, A.; Testani, E.; Montemurro, F. Sustainability of agro-ecological practices in organic horticulture: Yield, energy-use and carbon footprint. *Agroecol. Sustain. Food Syst.* **2020**, *44*, 726–746. [CrossRef]
46. Antichi, D.; Sbrana, M.; Martelloni, L.; Abou Chehade, L.; Fontanelli, M.; Raffaelli, M.; Mazzoncini, M.; Peruzzi, A.; Frasconi, C. Agronomic performances of organic field vegetables managed with conservation agriculture techniques: A study from Central Italy. *Agronomy* **2019**, *9*, 810. [CrossRef]

47. Hiltbrunner, J.; Liedgens, M.; Bloch, L.; Stamp, P.; Streit, B. Legume cover crops as living mulches for winter wheat: Components of biomass and the control of weeds. *Eur. J. Agron.* **2007**, *26*, 21–29. [CrossRef]
48. Wezel, A.; Casagrande, M.; Celette, F.; Vian, J.F.; Ferrer, A.; Peigné, J. Agroecological practices for sustainable agriculture. A review. *Agron. Sustain. Dev.* **2014**, *34*, 1–20. [CrossRef]
49. Diacono, M.; Persiani, A.; Castellini, M.; Giglio, L.; Montemurro, F. Intercropping and rotation with leguminous plants in organic vegetables: Crop performance, soil properties and sustainability assessment. *Biol. Agric. Hortic.* **2021**, *37*, 141–167. [CrossRef]
50. Baldi, E.; Toselli, M.; Marcolini, G.; Quartieri, M.; Cirillo, E.; Innocenti, A.; Marangoni, B. Compost can successfully replace mineral fertilizers in the nutrient management of commercial peach orchard. *Soil Use Manag.* **2010**, *26*, 346–353. [CrossRef]
51. Pane, C.; Celano, G.; Piccolo, A.; Villecco, D.; Spaccini, R.; Palese, A.M.; Zaccardelli, M. Effects of on-farm composted tomato residues on soil biological activity and yields in a tomato cropping system. *Chem. Biol. Technol. Agric.* **2015**, *2*, 4. [CrossRef]
52. Blengini, G.A. Using LCA to evaluate impacts and resource conservation potential of composting: A case study of the Asti District in Italy. *Resour. Conserv. Recycl.* **2008**, *52*, 1373–1381. [CrossRef]
53. Martínez-Blanco, J.; Muñoz, P.; Anton, A.; Rieradevall, J. Life cycle assessment of the use of compost from municipal organic waste for fertilisation of tomato crops. *Resour. Conserv. Recycl.* **2019**, *53*, 340–351. [CrossRef]
54. Pergola, M.; Persiani, A.; Palese, A.M.; Di Meo, V.; Pastore, V.; D'Adamo, C.; Celano, C. Composting: The way for a sustainable agriculture. *Appl. Soil Ecol.* **2018**, *123*, 744–750. [CrossRef]
55. Saer, A.; Lansing, S.; Davitt, N.H.; Graves, R.E. Life cycle assessment of a food waste composting system: Environmental impact hotspots. *J. Clean. Prod.* **2013**, *52*, 234–244. [CrossRef]
56. Pampuro, N.; Dinuccio, E.; Balsari, P.; Cavallo, E. Evaluation of two composting strategies for making pigslurry solid fraction suitable for pelletizing. *Atmos. Pollut. Res.* **2016**, *7*, 288–293. [CrossRef]
57. Colón, J.; Martínez-Blanco, J.; Gabarrell, X.; Artola, A.; Sánchez, A.; Rieradevall, J.; Font, X. Environmental assessment of home composting. *Resour. Conserv. Recycl.* **2010**, *54*, 893–904. [CrossRef]
58. Di Maria, D.; Sisani, F. Greenhouse gas emissions and environmental impact from recycling the organic fraction of solid waste: Comparison of different treatment schemes from a life cycle perspective. *Recycling* **2017**, *2*, 13. [CrossRef]
59. Navarro-Miró, D.; Iocola, I.; Persiani, A.; Blanco-Moreno, J.M.; Lakkenborg Kristensen, H.; Hefner, M.; Tamm, K.; Bender, I.; Védie, H.; Willekens, K.; et al. Energy flows in European organic vegetable systems: Effects of the introduction and management of agroecological service crops. *Energy* **2019**, *188*, 116096. [CrossRef]
60. Diacono, M.; Persiani, A.; Canali, S.; Montemurro, F. Agronomic performance and sustainability indicators in organic tomato combining different agroecological practices. *Nutr. Cycl. Agroecosyst.* **2018**, *112*, 101–117. [CrossRef]
61. Persiani, A.; Montemurro, F.; Fiore, A.; Scazzarriello, R.; Diacono, M. On-farm fertilizing materials in organic horticulture: Agronomic performance, energy use and GHG emissions evaluation. *Arch. Agron. Soil Sci.* **2020**, 1–17. [CrossRef]
62. Zhou, J.; Li, B.; Xia, L.; Fan, C.; Xiong, Z. Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefit for intensive vegetable production. *J. Clean Prod.* **2019**, *225*, 984–994. [CrossRef]
63. Jia, J.X.; Maa, Y.C.; Xiong, Z.Q. Net ecosystem carbon budget, net global warming potential and greenhouse gas intensity in intensive vegetable ecosystems in China. *Agric. Ecosyst. Environ.* **2012**, *150*, 27–37. [CrossRef]
64. Hwang, H.Y.; Kim, G.W.; Kim, S.Y.; Haque, M.M.; Khan, M.I.; Kim, P.J. Effect of cover cropping on the net global warming potential of rice paddy soil. *Geoderma* **2017**, *292*, 49–58. [CrossRef]
65. Guardia, G.; Aguilera, E.; Vallejo, A.; Sanz-Cobena, A.; Alonso-Ayuso, L.; Quemada, M. Effective climate change mitigation through cover cropping and integrated fertilization: A global warming potential assessment from a 10-year field experiment. *J. Clean. Prod.* **2019**, *241*, 118307. [CrossRef]
66. Kaye, J.P.; Quemada, M. Using cover crops to mitigate and adapt to climate change. A review. *Agron. Sustain. Dev.* **2017**, *37*, 4. [CrossRef]
67. De Benedetto, D.; Montemurro, F.; Diacono, M. Impacts of agro-ecological practices on soil losses and cash crop yield. *Agriculture* **2017**, *7*, 103. [CrossRef]