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ORIGINAL ARTICLE

Suitability of different organic amendments from agro-industrial wastes in organic lettuce crops

Francesco Montemurro · Corrado Ciaccia · Rita Leogrande · Francesco Ceglie · Mariangela Diacono

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Abstract An inadequate replacement of organic matter in agricultural lands progressively leads to soil fertility reduction and therefore, soil application of organic fertilizers and amendments should be promoted. The objectives of this 3-year research project on organic lettuce were to investigate the agronomic performance of experimental organic amendments obtained by using agro-industrial wastes in comparison with a commercial organic fertilizer, and to evaluate their short-term effects on soil mineral-N and soil organic carbon changes. Two types of olive pomace mixtures, with different initial C/N ratios, were composted and either stopped at the active phase (A1 and B1) or processed until maturation (A2 and B2). Also an anaerobic digestate (DA) and the B2 in combination with mineral fertilizer (B2-MIN) were studied. The four composts, DA and B2-MIN were compared with a commercial organic fertilizer (Org), and an unfertilized control (N0). Results suggested that the best compromise for organic lettuce yield and soil fertility could be obtained with the B2 compost, thus highlighting the need for choosing a good stage of maturity of the compost, along with an appropriate C/N ratio of composting mixture, to improve the fertilizing efficiency of agro-food residues in organic farming. Furthermore, the application of immature amendments did not increase (B1) or significantly reduce (A1) marketable lettuce yield, indicating that the choice of organic fertilizer is an important concern in sustainable agriculture, especially in organic vegetable production.

Keywords Agro-food residues · Olive pomace compost · Anaerobic digestate · Organic farming · Agronomic performance

F. Montemurro
Research Unit for Cropping Systems in Dry Environments (Azienda Sperimentale Metaponto), Consiglio per la Ricerca e l'analisi dell'economia Agraria – CRA-SCA, Metaponto, MT, Italy

C. Ciaccia
Research Centre for the Soil–Plant System, Consiglio per la Ricerca e l'analisi dell'economia Agraria – CRA-RPS, Roma, Italy

R. Leogrande · M. Diacono (✉)
Research Unit for Cropping Systems in Dry Environments, Consiglio per la Ricerca e l'analisi dell'economia Agraria – CRA-SCA, Via Celso Ulpiani 5, 70125 Bari, Italy
e-mail: mariangela.diacono@entecra.it

F. Ceglie
CIHEAM – MAIB, Mediterranean Agronomic Institute of Bari, Valenzano, BA, Italy

Introduction

Soil organic matter is a very reactive quality indicator that influences the productivity of soil (Komatsuzaki and Ohta 2007), by improving its physical, chemical and biological properties (Sequi 1989). Warm climate conditions and agricultural intensification tend to increase the rate of decomposition of organic substances in soil, for example in the Mediterranean environment (Montemurro et al. 2007). This decomposition determines the release and cycling of plant nutrients and, therefore, an inadequate replacement of organic matter in agricultural lands progressively leads to the degradation of important properties of the soil and, in the long term, reduces soil fertility.

Van-Camp et al. (2004) indicated that the build-up of soil organic matter is a much slower and more complex process than its decline. As a consequence, to preserve or increase organic matter in soil, application of organic fertilizers and amendments (e.g., manure, agro-industrial by-products and compost) should be promoted (Cayuela et al. 2010). This approach is particularly crucial in organic farming, which avoids the use of synthetic fertilizers and promotes the use crop rotations, organic fertilizers and soil amendments (Maeder et al. 2002; Diacono and Montemurro 2011).

Olive pomace, which is one of the most important organic agro-industrial wastes in Mediterranean countries, contains a large proportion of organic matter that could profitably be recycled (Diacono et al. 2012). Altieri and Esposito (2010) indicated that composting is recognized as an environment-friendly and economically viable technology for managing organic waste such as olive mill wastes. Moreover, the winery industry produces large amounts of organic residues and effluents that can be transformed by anaerobic micro-organisms into lower molecular weight organic compounds and biogas (Montemurro et al. 2010). According to Alburquerque et al. (2012a), the obtained anaerobic digestate contains considerable amounts of residual organic carbon and plant nutrients and it is characterized by having a high mineralization rates in the soil. Compost and anaerobic digestate are among the most widespread organic materials, which can be considered valuable resources to support soil fertility (Tejada et al. 2009; Alburquerque et al. 2012b).

However, there is a lack of knowledge on the effects of applying olive pomace compost and digetates on horticultural crops, particularly in organic farming. In addition, although the response of lettuce crops to organic waste application has been reported in several studies, in both field (Montemurro 2010) and greenhouse (Dolgen et al. 2004) trials, there is a lack of scientific evidence of their use in organic cultivation.

In the light of these considerations, the objectives of this 3-year field trial, on lettuce cropped under organic farming management and Mediterranean conditions, were: (1) to investigate the agronomic performance of different experimental organic amendments in comparison with a commercial organic fertilizer; (2) to evaluate the short-term effects of the tested organic materials application on soil mineral nitrogen and changes in soil organic carbon.

Materials and methods

Compost mixtures, composting set-up and analytical determinations

Olive pomace was collected from two-phase centrifugation olive oil milling industries in Apulia region (Southern Italy). Two olive pomace composts (OPC) were made in 2008 and 2009, by mixing pruning wastes (as bulking agent) and cattle manure, as nitrogen (N) source, with the olive pomace, to produce two different composting mixtures that were processed in bio-containers: one mixture (A) with a high C/N ratio, equal to 45; and another one (B), with a somewhat lower C/N ratio, equal to 30. At the end of the active phase, each mixture was removed from the bio-containers and split outdoors in two heaps. One heap of each mixture was sun-dried in a thin layer (2.5 cm) to produce A1 and B1 composts, respectively, whilst the second heap was led to maturation in a turned windrow, thus obtaining A2 and B2, respectively. The bio-oxidative phase was considered finished when the temperature of the mixture was stable, close to the external value, with no reheating. As a consequence, two types of OPC, with different initial C/N, were obtained: stopped at the active phase (A1 and B1) and processed until maturation (A2 and B2). More details are available in Diacono et al. (2012).

Compost samples for the analyses were obtained by mixing six sub-samples from each heap and pooled in three sub-samples. The main chemical characteristics of the obtained OPC are shown in Table 1. Since we did not find significant differences among composts between years, the mean of the compost properties are reported. The moisture content (%) was determined by drying each sample at 105 °C until constant weight was reached. The pH was measured in a 1:10 (w/v) compost/water mixture at 24 ± 1 °C. The total

Table 1 Main chemical characteristics of the experimental and commercial organic fertilizers

Parameters	Experimental organic fertilizers					Commercial organic fertilizer
	A1	A2	B1	B2	DA	Org
Moisture (%)	10.5 ± 0.17	47.8 ± 7.86	9.80 ± 4.24	44.5 ± 3.29	66.0 ± 0.29	12.0
pH	7.19 ± 0.21	7.48 ± 0.33	7.36 ± 0.25	8.51 ± 0.39	7.63 ± 0.31	7.3
TOC (g kg^{-1})	395 ± 19.2	382 ± 17.9	381 ± 13.4	363 ± 13.5	192 ± 21	410
Total P (g kg^{-1})	3.26 ± 0.79	3.94 ± 0.84	6.02 ± 1.21	6.28 ± 1.32	1.17 ± 0.62	4.0
Total N (g kg^{-1})	13.8 ± 3.31	17.9 ± 4.23	16.3 ± 3.36	19.3 ± 3.62	30.3 ± 1.22	40.0
C/N	28.60	21.35	23.44	18.82	6.34	10.2

Reported values are the mean of the 2-year analytical results ± standard deviation (A1, A2, B1, B2, DA) or those provided by the manufacturer (Org)

A1: compost, from mixture with a high C/N ratio, stopped at the active phase, and A2: processed until maturation; B1: compost, from mixture with lower C/N ratio, stopped at the active phase, and B2: processed until maturation; DA: anaerobic digestate based on wine distillery waste water; Org: commercial organic fertilizer

organic carbon (TOC, g kg^{-1}) was measured by dichromate oxidation, while nitrogen (N, g kg^{-1}) was analyzed according to the Kjeldahl method (Bremner and Mulvaney 1982). Total P content (mg kg^{-1}) was determined by Inductively Coupled Plasma-Optical Emission spectrometry (ICP-OES) after digestion in 65 % HNO_3 in a pressurized oven (Page et al. 1982).

Site of study, experimental design and measurements

The research was carried out on a field located at the experimental farm 'Azienda Sperimentale Metaponto', of the Consiglio per la Ricerca e la sperimentazione in Agricoltura - Research unit for cropping systems in dry environments, CRA-SCA (ASM), at Metaponto (MT), in Southern Italy (40°24′N; 16°48′E and 8 m above sea level). The climate is "accentuated thermomediterranean", as classified by UNESCO-FAO (1963), with winter temperatures which can fall below 0 °C, summer temperatures which can rise above 40 °C and rainfall unevenly distributed during the year, being concentrated mainly in the winter months. In Fig. 1 the monthly mean temperatures and the rainfall for each lettuce cropping season were compared with the long-term averages (30 years). The total amounts of rainfall, recorded during the three cropping cycles, were 190, 144 and 293 mm in 2009, 2010 and 2011, respectively, i.e. higher by 57, 19 and 142 % than the corresponding long-term averages.

During the experimental trial, the mean temperatures in 2009, 2010 and 2011 were 14.9, 16.4 and 11.5 °C, respectively. Therefore, only in 2011 the mean temperature value was notably lower than that of the long-term period (16 °C).

The soil, classified as a Typic Epiaquert (Soil Survey Staff, 1999), contains 1.0 g kg^{-1} of N and 19.0 g kg^{-1} of organic matter, 759 mg kg^{-1} of exchangeable potassium (K), 31.1 mg kg^{-1} of Olsen available phosphorus (P), and has a pH value of 8.4. Clay and silt contents are 60 and 36 %, respectively, and electrical conductivity (1:10 (w/v) water-soluble extraction) is 0.48 dS m^{-1} at 0–30 cm depth, increasing with depth. Cation exchange capacity is 27.1 meq 100 g^{-1} of dry soil, with 15.5 and 8.6 meq 100 g^{-1} of calcium and magnesium, respectively. Soil water content is 34.5 and 20.1 % (as a percentage of soil-dry weight) at field capacity (−0.03 MPa) and permanent wilting point (−1.5 MPa), respectively. The average soil bulk density is 1350 kg m^{-3}.

Within a 3-year spinach–lettuce rotation with the same experimental design and crop management, lettuce (*Lactuca sativa* var. longifolia Lam. cv Bacio) plants were transplanted by hand in mid-March in each year, replacing spinach in the rotation. The same plots were used in each season to cultivate lettuce to study the cumulative effect on soil, and to avoid the possible confounding effect of sites on treatments. The harvest occurred in the last week of May in 2009 and in the first week of June in 2010 and 2011.

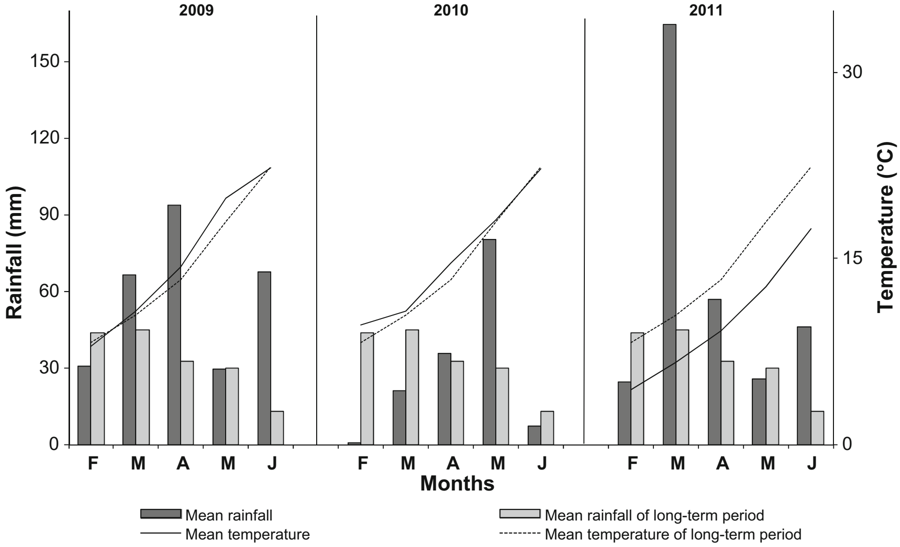

Fig. 1 Mean monthly temperatures and rainfall during the lettuce cropping cycles (2009, 2010, 2011) in comparison to the mean long-term values (30 years)

In a randomized complete block experimental design with three replications, the above-mentioned OPC treatments (A1, A2, B1 and B2) were studied. Moreover, we investigated an anaerobic digestate based on wine distillery waste water (DA) and further tested B2 by applying it in combination with mineral fertilizer (B2-MIN) i.e., 50 % of total fertilizer N input was applied as organic fertilizer (B2) before transplanting and 50 % as ammonium nitrate during the cropping cycle. The four composts, the DA and B2-MIN were also compared with a commercial organic fertilizer (Org) and an unfertilized control (N0). All fertilizer treatments received 140 kg ha^{-1} of N. Organic materials were applied about 1 month before lettuce transplanting, and immediately tilled into the soil (about 15 cm depth). Each plot consisted of 15 m^2 (5 × 3 m).

At harvest, lettuce plants were taken from the middle of each plot (1 m^{-2} of test area) for measuring marketable yield (t ha^{-1}), total dry matter (48 h at 70 °C; t ha^{-1}), marketable head weight (g) and LAI. Furthermore, 5 plants were randomly taken up from each plot to determine nitrate content (NO_3^-–N, mg kg^{-1}) using Nitracheck® reflectometer (MERCK). Dry matter of the same plants was used to measure the total N (%) content (Kjeldahl method). This last measurement allowed the calculation of N uptake (N content × total dry weight) and the nitrogen utilization efficiency index (NUE) as the ratio of yield to N uptake (kg kg^{-1}), according to Montemurro (2010) terminology.

Soil mineral nitrogen (mg kg^{-1}, nitrate–N and ammonium–N) was determined at the beginning (t0) and during the cropping cycles (t1: about 25 days after transplanting; t2: at harvesting time). Nitrate–N and ammonium–N (NO_3^-–N + NH_4^+–N) were extracted by 2 M KCl (1:10 w/v; shaken for 60 min) and determined by continuous flowing system according to Krom (1980) and Henriksen and Selmer-Olsen (1970), respectively. The total organic carbon (TOC, g kg^{-1}) was measured by dichromate oxidation, then, taking into account the soil bulk density, soil carbon data were expressed as tonnes per hectare in the 0–30 cm layer.

Statistical analysis

The statistical analysis was carried out using the General Linear Model procedure (PROC GLM) of the SAS package (Sas Institute 2012). The years and replications were considered as random effect, whereas N fertilizing management as fixed one. The differences among the experimental treatments were analyzed at the $P \leq 0.05$ probability level, by applying the Student–Newman–Keuls test. The differences found with the test for different main effect and interaction comparisons were calculated using the appropriate standard error term.

Results

Characteristics of the experimental composts

At the end of the active phase and after sun-drying, A1 and B1 showed lower moisture percentage compared to both the matured composts (A2 and B2) and to the anaerobic digestate (Table 1), but comparable to Org. The A1, A2, B1 compost and DA had comparable values of pH, whereas B2 showed a significantly higher level for this parameter. The TOC content of all the composts was higher than 350 g kg^{-1}, whereas a value lower than 200 g kg^{-1} was observed in the DA fertilizer. The total *P* was significantly higher in B1 and B2 than in the two A composts, and it was higher in all experimental composts than in DA. Conversely, the latter organic fertilizer showed the highest level of total N, which was particularly greater than in the composts stopped at the active phase (A1 and B1). The C/N ratio was above the threshold of 25 only for A1, as a consequence of its low level of total N.

Crop yield and N status parameters

The output of the analysis of variance revealed significant main effects of years and fertilizer treatments (except leaf nitrate content) on lettuce crop yield and quality parameters, LAI and N status indices at harvesting. A significant interaction between years and fertilizer strategies was found only for marketable yield and marketable head weight, indicating the year dependency of fertilizer treatments effects on these variables.

On the whole, the best marketable yield and head weight performance were observed in the third year and the worst in the first year (Table 2). On average, the greatest yield value was found for B2-MIN, closely followed by the Org treatment. Both A1 and B1 showed the significantly lowest mean values, which were notably lower than the other treatments although B1 was comparable with N0. Therefore, it seems better to avoid their application in organic horticulture, as discussed in the next section.

In 2009, no significant differences in marketable yield were found among treatments other than A1 and B1. In particular, the A1 compost had a significantly lower yield than A2 and B2-MIN. In 2010, the B2-MIN showed the highest value, which was 71.4 % higher than the average of the other treatments (comparable among them). In 2011, both the B2-MIN and Org treatments gave the highest marketable yields, B2 and DA showed intermediate values, whereas N0 gave a value comparable to A2 and B1 and higher than A1.

With regard to the marketable head weight in 2009, high and comparable values were found among B2-MIN, Org, DA and B2. In particular, B2-MIN had a value higher by 134 % than the average of A2 and N0, which showed intermediate values, whilst A1 and B1 gave the lowest values (Table 2). In the second season, no significant differences were observed among treatments except between B2-MIN and A1. Finally, in 2011, the best performances were found in B2-MIN and Org, particularly B2-MIN which had a marketable head weight higher by 180 % than the average of A1, A2 and B1. An intermediate value was found for DA. On the whole, the significantly highest 3-year averages of marketable head weight were observed for B2-MIN and Org, whereas intermediate values were obtained for DA and B2.

The lowest lettuce total dry matter (1.09 t ha^{-1}) and LAI (2.19) values were found in 2009, there were intermediate values in 2011 (1.82 and 3.02 t ha^{-1}, respectively), whereas the highest values of these two parameters were found in 2010 (1.9 and 3.57 t ha^{-1}, respectively) (data not shown). Figure 2 shows the effects of fertilizer treatments on dry matter and LAI at harvesting, as means of 3 years. The B2-MIN showed the highest absolute value of total dry matter, which, however, was comparable to both Org and DA treatments. The lowest value was found for A1, whereas the other treatments showed intermediate values. The LAI values confirmed the best overall results for B2-MIN, Org and DA.

In Table 3 the effects of years and fertilizers on lettuce N status parameters and indices are reported, as means of the 3-year period. In 2011, leaf nitrate content and N uptake had significantly highest values, as compared to the other 2 years, which did not differ significantly from each other. The highest and the lowest N contents were found in 2009 and 2010, respectively. Finally, NUE was higher, both in 2010 and 2011, than in 2009. No significant differences were found for nitrate contents of lettuce leaves among treatments. The highest N content results were observed in A1, A2 and B2, even though comparable to DA and N0 treatments. The highest N uptake was found with B2-MIN treatment, even though

Table 2 Mean values of fertilizing strategies (columns), years (rows) and "fertilizing strategies × years" interaction for lettuce marketable yield and marketable head weight

Years	A1	A2	B1	B2	DA	B2-MIN	Org	N0	Means
Marketable yield (t ha^{-1})									
2009	2.32c	22.6ab	4.60bc	14.0abc	17.6abc	23.8a	17.2abc	10.9abc	14.1c
2010	10.2b	15.4b	16.3b	18.5b	19.2b	27.5a	18.2b	14.5b	17.4b
2011	8.89d	12.2dc	14.4dc	22.9b	24.8b	34.4a	35.5a	16.3c	21.2a
Means	7.14f	16.7cd	11.8e	18.5c	20.5bc	28.5a	23.6b	13.9de	17.5
Marketable head weight (g)									
2009	32.6e	110ce	80.3de	192ad	247ac	334a	275ab	177be	181c
2010	158b	225ab	246ab	272ab	287ab	368a	277ab	233ab	259b
2011	112e	189de	213de	334bc	354b	480a	521a	238 cd	305a
Means	101d	175c	180c	267b	296b	394a	358a	216c	248

The values of the means of both fertilizing strategies (columns) and years (rows) and of the interaction "fertilizing strategies × years" with same letter are not significantly different according to the SNK at the $P \leq 0.05$ probability level

Analysis of variance for marketable yield; probability levels: Years (Y) significant at the $P < 0.01$; Fertilizer strategies (F) significant at the $P < 0.001$; Y × F significant at the $P < 0.05$

Analysis of variance for marketable head weight; probability levels: Years (Y) significant at the $P < 0.001$; Fertilizer strategies (F) significant at the $P < 0.001$; Y × F significant at the $P < 0.05$

Treatments: A1: compost, from mixture with a high C/N ratio (45), stopped at the active phase, sun-dried in a thin layer, and A2: processed until maturation as a turned windrow; B1: compost, from mixture with lower C/N ratio (30), stopped at the active phase, and B2: processed until maturation; DA: anaerobic digestate based on wine distillery waste water; B2-MIN: 50 % as B2 in combination with 50 % of mineral fertilizer (ammonium nitrate); Org: organic commercial fertilizer; N0: unfertilized control

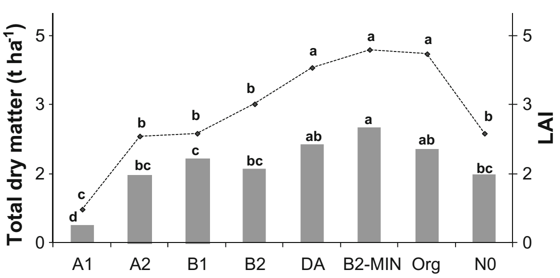

Fig. 2 Effects of fertilizer treatments on lettuce total dry matter (*histogram*) and LAI (*dotted line*) at harvesting over 3 years. *Note* Analysis of variance for total dry matter; probability levels: Years (Y) significant at the $P < 0.001$; Fertilizer strategies (F) significant at the $P < 0.001$; Y × F not significant. Analysis of variance for LAI; probability levels: Years (Y) significant at the $P < 0.001$; Fertilizer strategies (F) significant at the $P < 0.001$; Y × F not significant. Treatments: see footnotes of Table 2

comparable to B2, DA and Org fertilizers, whilst A1 showed the lowest value. In particular, the B2-MIN showed N uptake higher by 63 and 114 %, than N0 and the average of A2 and B1 treatments, respectively. The NUE value of A1 was significantly higher than those of A2, DA and N0, whereas it was comparable to the other treatments.

Effects of fertilizer treatments on soil mineral nitrogen contents at different stages and on soil organic carbon changes

The output of the analysis of variance revealed significant main effects of years on all the soil parameters tested, and of fertilizer treatments on soil nitrate–N and soil exchangeable ammonium. No significant interactions between years × fertilizer strategies were found in the tested variables.

In Fig. 3 the changes in the concentration of soil mineral N are displayed as the sum of soil nitrate–N and exchangeable ammonium, as 3 years averages, at the beginning (t0) and during the cropping cycle at the t1 and t2 stages.

At t0, the soil mineral N showed the highest value on Org plots, which was similar only to the B2-MIN value, even though the latter had a nitrate component lower by 38 % than in Org.

Moreover, at this initial stage, soil mineral N in B2 was lower by 82 % than in Org, whereas all the other treatments had similar intermediate contents. At t1, B2-MIN showed the highest value, as compared to all the other (comparable among them) treatments, which

Table 3 Effects of years and fertilizer treatments on lettuce N status parameters and indices

	Nitrate (leaves) mg kg^{-1}	N content g kg^{-1}	N uptake kg ha^{-1}	NUE kg kg^{-1}
Years				
2009	40.2b	2.79a	24.6b	46.7b
2010	29.0b	1.61c	30.3b	65.8a
2011	55.6a	2.15b	38.1a	61.7a
	***	***	***	*
Fertilizer				
A1	44.9	2.40a	8.55d	83.7a
A2	46.5	2.44a	24.7c	48.8b
B1	39.4	2.01b	20.9c	55.0ab
B2	43.6	2.39a	37.4ab	59.8ab
DA	40.8	2.10ab	43.1ab	48.5b
B2-MIN	28.5	1.94b	48.8a	60.3ab
Org	40.6	1.84b	38.6ab	63.9ab
N0	48.4	2.13ab	30.0bc	47.7b
	n.s.	***	***	*

Within fertilizing treatments, the values in each column followed by same letter are not significantly different at $P \leq 0.05$ (SNK). The probability levels of analysis of variance are presented by years (Y) and organic fertilizer strategies (F). *; ***, n.s. significant at the $P < 0.05$, 0.001, respectively. n.s. not significant. Y × F interactions were all not significant. Treatments: see footnotes of Table 2

was due to its highest contents of both nitrate and ammonium. Finally, at t2, the soil mineral N value in B2-MIN was significantly higher (by 68 %) than in A1, but comparable to all the other treatments. In addition, at this stage, the mixed treatment showed a higher ammonium component than that of nitrate.

At the end of the field trial, the repeated application of organic fertilizers (i.e., different C inputs) in the lettuce cropping seasons revealed a change in the content of soil organic carbon (Table 4). In particular, A2, B1 and B2 showed increases in C content, whereas decreases were found in Org, followed by DA and A1.

Discussion

Characteristics of the experimental composts and identified drawbacks

The total N and P contents of the four experimental composts were quite different, suggesting that the composition of starting materials may be responsible for the nutrient contents of amendments, as reported in detail by Diacono et al. (2012). The pH of the composts was in the range allowed by Italian fertilizers legislation, which is 6–8.5 (Decree n. 75 2010). Moreover, the TOC contents exceeded (by 81–97 %) the minimum value of 200 g kg^{-1} established by that legislation. However, not all the produced composts were optimal for lettuce cultivation and choosing the stage of maturity of the composting mixture seemed to be among the essential practices for compost use. Both composts stopped at the active phase of the composting process (A1 and B1) gave non-sustainable yield results under our field trial conditions, despite B1 performed poorly in 1 year and better in the other 2 years likely due to erratic climatic conditions influencing its mineralization. In addition, the reduced biomass in A1 and B1 highlighted a concentration effect in the canopy for the crop N content and N uptake values (Delogu et al. 1998). Similarly, Buchanan (2012) found that the mature composts resulted in better yields in organic vegetables. In the long term, the A1 compost could also lead to soil fertility reduction, as shown by SOC changes at the end of the field trial, in comparison with the other composts. Moreover, the higher C/N ratio in A1 than in B1, and its lowest N content, could induce soil N immobilization (Corbeels et al. 1999). This is a possible explanation for the lowest soil mineral-N found at the end of the 3-year period in A1 plots. Due to all these drawbacks, A1 and B1 should not be considered for use for lettuce production, therefore, a comparative analysis will be done for the two mature composts (A2 and B2) with DA, Org and N0 treatments.

Effects of fertilizer treatments on lettuce crop and soil properties

In the study site, lettuce productive responses to organic fertilization were influenced by climatic conditions from year to year, which likely affected the mineralization rate and N supply (Diacono and Montemurro 2011). In particular, it is suggested that in 2011 the high rainfall at transplanting could have caused a faster absorption of the N supplied in the long term, thus ensuring a higher crop production than in the other years. By contrast, despite the more balanced rainfall during 2009, the availability

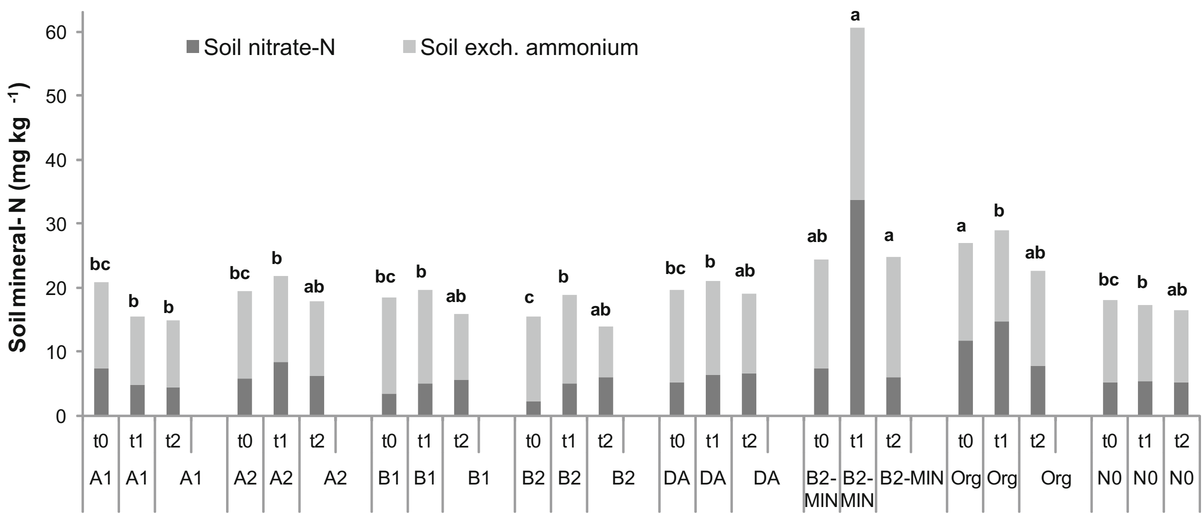

Fig. 3 Changes in the concentration of soil mineral N (mg kg^{-1}) displayed as the sum of soil nitrate–N and exchangeable ammonium on the 3 years average, divided by fertilizer treatments: at the beginning (t0) of the cropping cycle; at t1: about 25 days after transplanting; at t2: harvesting time. Same letters indicate mean values not significantly different according to Duncan at the $P \leq 0.05$ probability level. *Note* Analysis of variance for soil nitrate–N; probability levels: Years (Y) significant at the $P < 0.001$; Fertilizer strategies (F) significant at the $P < 0.001$; Y × F not significant. Analysis of variance for soil exchangeable ammonium; probability levels: Years (Y) significant at the $P < 0.001$; Fertilizer strategies (F) significant at the $P < 0.05$; Y × F not significant. Analysis of variance for soil mineral N; probability levels: Years (Y) significant at the $P < 0.05$; Fertilizer strategies (F) and Y × F: not significant. Treatments: see footnotes of Table 2

Table 4 Soil organic C (SOC) changes in the 0–30 cm layer after 3 years of organic fertilizers application

Parameters	Organic fertilizers					
	A1	A2	B1	B2	DA	Org
Fertilizer rate (t ha^{-1})	12.3	13.0	10.9	10.8	4.4	1.2
C input (t ha^{-1})	19.7	20.2	16.8	15.8	3.42	1.99
Initial SOC (t ha^{-1})	60.1	60.1	60.1	60.1	60.1	60.1
Final SOC (t ha^{-1})	59.9	63.2	63.2	62.4	57.1	44.1
SOC changes (t ha^{-1})[a]	−0.20c	3.04a	3.04a	2.23b	−3.04d	−16.0e

[a] Final SOC–Initial SOC
Treatments: see footnotes of Table 2

of nutrients by organic fertilizers was at a lower level due to the single dose applied. These results substantiate findings of Tittarelli et al. (2007), who pointed out that the slow release of nutrients by organic materials is responsible for the increase in crop yields in subsequent years.

The mixed fertilizer (B2-MIN) gave the highest marketable yield on the average of the 3 years, and marketable head weight comparable to Org, generally showing good productive performance during each trial year. Furthermore, the total dry matter and N status parameters confirmed these outcomes, suggesting that it is possible to partially substitute mineral N with organic N fertilizer, in accordance to findings of Montemurro et al. (2006) on other crops. At the end of the experiment, the B2-MIN treatment showed a high soil mineral N, mainly composed of soil exchangeable ammonium, showing a nitrate–N component lower by 23 % than in Org. This could be considered a positive result, but it is necessary to take into account also the result at the t1 stage (about 25 days after transplanting). At this stage, the nitrate content was more than 100 % higher than in Org plots, indicating a risk of groundwater pollution due to nitrate losses by leaching. Moreover, the B2-MIN required splitting the application in two, i.e., 50 % as B2 before transplanting and 50 % as ammonium nitrate during the cropping cycle, therefore, it involved increased distribution costs (in comparison with composts with single application), thus further reducing its sustainability.

By contrast, the DA and B2 treatments showed intermediate and consistent yield results during the field trial, as well as intermediate dry matter, LAI, and good N content, N uptake, and NUE outcomes, suggesting the possibility to use these alternative fertilizers to support lettuce crop production by substituting traditional fertilization. These results are consistent with the findings reported by other authors in other crops (Altieri and Esposito 2010; Montemurro et al. 2010). Moreover, they are further supported by the soil mineral N results, which highlighted that DA and B2 had comparable behavior than Org, both at t1 and t2 stages. Anyway, C dynamics findings could lead to a forced choice between the two experimental fertilizers (DA and B2). As a matter of fact, any attempt to enrich the organic carbon reservoir through sequestration of atmospheric C will help to reduce global warming, therefore, A2 and B2 have positive results for C dynamics (increasing SOC on average by 4.5 %) that are of crucial importance. Fertilization with mature composts increases the amount of hydrophobic compounds that protect the biolabile soil carbon from mineralization, thereby enhancing the carbon sink capacity of SOM (Spaccini et al. 2002, 2009). This outcome of compost on soil organic matter increase and stabilization could be particularly useful in Mediterranean areas, where the climatic conditions generally induce high mineralization. In our research, the observed effects of composted organic materials on SOC changes further confirm findings of other studies (Kukal et al. 2009; Diacono et al. 2012). Conversely, the DA repeated applications reduced the SOC content, thus contributing in the long term to both an atmospheric enrichment in CO_2 concentration and a reduction in soil fertility. Similarly, results of Saviozzi et al. (1999) on digested sewage sludge over 12 years indicated that such organic amendment was inadequate for the restoration of organic matter lost as a consequence of cultivation. Also the Org treatment caused a decline in SOC, confirming other findings on C depletion in the top soil layers with organic fertilizers other than compost (Nardi et al. 2004). Similarly, Albiach et al. (2001) found that after repeated organic residues applications, there was a significant increase in humified substances in the soil, whereas commercial organic amendments did not produce any significant change.

From all of the above, it may be concluded that the best compromise for lettuce yield, soil, and environmental results can be obtained by using a composting mixture with a low C/N ratio processed until maturation, such as the B2 compost. This compost also had N and P contents higher by 21.5 and 74.4 %, respectively, than those on average of the A mixtures, probably due to the highest amount of cattle manure in the composting mixture (Diacono et al. 2012).

Conclusion

Soil application of processed agro-industrial by-products may sustain crop production and soil fertility in Mediterranean soils, especially for vegetables which complete their cropping cycles in a relatively short period of time. This is particularly true in organic farming, since these amendments can contribute to closing the natural ecological cycles.

The results of this research indicated that the use of mature compost from a mixture with a low C/N ratio (B2) appeared to be the most suitable for organic lettuce, which is characterized by its short growing period, since it gets a favorable trade-off among yield, product quality, N-use efficiency and environmental impact, particularly under Mediterranean conditions.

However, it is necessary to choose a good stage of maturity of the compost, to improve the fertilizing efficiency of composted agro-food residues in organic farming, as well as an appropriate C/N ratio as a compost starting requirement. Otherwise, the indiscriminate (total or) partial substitution of mineral N with organic N fertilizer may be non-sustainable.

Further studies are needed to evaluate long-term effects of the tested amendments, so to step up the awareness of the stakeholder community involved in organic lettuce cultivation on the need to choose appropriate organic fertilizers.

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