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Municipal solid waste composting: Application as a tomato fertilizer and its effect on crop yield, fruit quality and phenolic content

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Abstract

Composting is an appealing way to reutilize the organic fraction of municipal solid waste (MSW). Beyond the obvious advantage of reducing urban waste, the use of MSW compost in agriculture entails other potential benefits, such as reducing the amount of mineral fertilizer applied to the field and providing a potentially higher quality alternative. However, some concerns may arise from its use, such as crop yield and quality alterations. This work studied the effect of fertilizing with compost obtained from the organic fraction of MSW, on crop yield, crop quality and phenolic content of tomato fruit. Experiments were conducted in the Barcelona area, using *Solanum lycopersicum* L., var. 'Penjar', a popular regional tomato. Compared with the use of mineral fertilizer (M), fertilization with MSW compost alone (C) or combined with mineral fertilizer (C + M) had no significant effect on tomato fruit quality characterized by weight, diameter or Brix, nor was there a significant effect on total phenolic content. In contrast, the C treatment altered the phenolic profile by enhancing a kaempferol derivative, and caused a 43 and 48% yield reduction compared with the C + M and M treatments, respectively. Overall, composted MSW + mineral fertilizer appeared to be the best strategy for the reutilization of MSW in tomato culture, as it did not compromise crop yield or fruit quality.

Key words: municipal solid waste, compost, tomato, fertilization, Penjar, crop yield, phenolic compounds, fruit quality

Introduction

Composting the organic fraction from municipal solid waste (MSW) is a sustainable way to manage and recycle urban waste and is a potentially viable source of high quality fertilizer. Indeed, several national and international directives encourage the maximal exploitation of MSW, with the aim of reducing the environmental impact and the loss of organic resources derived from urban refuse dumping (The Ninety-fourth United States Congress, 1976; Council of the European Union, 1999). Composted MSW is obtained by biological degradation of the organic substrates under aerobic conditions. The safe use of composted MSW in agriculture can be guaranteed if the organic matter source is properly sorted at the origin. Thus, good source management restricts the levels of heavy metals and other contaminants, producing a compost that meets quality standards for organic agriculture (Hargreaves et al., 2008).

Agricultural use of compost from the MSW organic fraction provides an interesting alternative to mineral fertilizers from a double standpoint: it is compatible with the increasing demand of agricultural commodities produced under sustainable practices, and it may lead to very positive changes in the soil. Concerning the latter, some reports have described how the continued use of compost can lead to favorable soil changes including increased moisture, organic matter and bulk density and the appearance of beneficial microorganisms (Elherradi

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et al., 2005; Martínez-Blanco et al., 2009), which ultimately result in better fruit quality and production rates. However, other reports have demonstrated that under certain conditions, compost fertilization induces lower production yields in comparison with mineral fertilization (Martínez-Blanco et al., 2011; Seufert et al., 2012). The detrimental effects may be due to the fact that nutrients in mineral fertilizer are very soluble and easily available to plants, while compost nutrients are in more complex forms and therefore less available.

Thus, the use of MSW compost in tomato production (*Solanum lycopersicum* L.) may result in changes not only in the production yield, but also in fruit growth and fruit quality. At the same time, the tomato phenolic profile may be affected (Treutter, 2010). Tomato phenolics deserve special attention for human health given that these compounds with antioxidant properties have been implicated in metabolic processes that may be important in reducing cancer and cardiovascular disease risk (Nijveldt et al., 2001; Crozier et al., 2009). For example, the high life expectancy of some Mediterranean countries has been linked to diets rich in fruits and vegetables, of which the tomato is a very common ingredient (Zamora-Ros et al., 2013). It has been demonstrated that tomato plants accumulate phenolic compounds as a defense mechanism under certain stress conditions, such as low N availability (Løvdal et al., 2010). An increase in tomato phenolic content has also been observed after organic amendment, such as compost fertilization (Mitchell et al., 2007; Brandt et al., 2011). Carotenoids, on the contrary, seem not to be affected by limited nutrient conditions (Brandt and Mølgaard, 2001; Caris-Veyrat et al., 2004).

This work studied the effect of fertilizing with compost from the MSW organic fraction on tomato yield, fruit quality and phenolic content, as part of an integrated strategy for the reutilization of MSW. The composting plant and the experimental field were located near Barcelona (Spain). The tested plants were of the 'Penjar' varietal type, which yields small-sized tomatoes with long shelf life that are very popular and widely consumed along the Spanish Mediterranean coast.

Materials and Methods

Field design and growth conditions

The experimental tomato plants were obtained from commercial seeds of the variety *Palamós*, 'Penjar' varietal type (Semillas Fitó, Barcelona, Spain). Plants were cultivated in an open-field system located in the Maresme region, Catalonia (northeast Spain, 41°38′27″N 2°43′00″ E, 10 m elevation). This region that borders the Mediterranean Sea is prolific in terms of horticultural production. The climate is typically Mediterranean, with an average temperature of 18.7°C and total rainfall equivalent to 165 mm^3 between March and August (Servei Meteorològic de Catalunya, 2015).

Plants were spaced 0.7–2.0 m apart, giving a density of 7142 plants·ha^{-1}. The soil of the experimental garden was a sandy loam. There was minimal usage of pesticides and herbicides, following the procedures accepted by the environmentally friendly regulations of the Integrated Cultivation Management (The Spanish Ministry of Agriculture, Fisheries and Food, 2002). Growing conditions were in accord with 'low input agricultural management' (Viaux, 2008). Following the regional standard conditions for 'Penjar' tomato cultivation, a plastic mulch layer was installed, plants were not staked and water was extracted from local wells and supplied via drip irrigation. Every treatment plot received 190 mm m^{-2} of water, in accordance with FAO guidelines (Allen et al., 1998) for cultures under plastic mulch and with specific water needs calculated on the basis of data obtained from tensiometers buried 30–60 cm underground.

Fertilization

Three different fertilization strategies were tested as follows: (i) M, mineral fertilizer only, (ii) C, MSW compost only and (iii) C + M, a combination of MSW compost and mineral fertilizer. The experimental design consisted of nine random blocks with three treatments and three repetitions each. Potassium nitrate (KNO_3) was used as a mineral fertilizer and delivered with the water supply. Compost for the C and C + M treatments was obtained from an industrial composting plant (Metrocompost, Castelldefels, Spain), which processed the MSW from an area near Barcelona with approximately 30,000 inhabitants. The raw compost material, which was mainly food waste, was sorted from the organic fraction of MSW. Pruning waste from parks and gardens was also added in a 1:1 *v*/*v* ratio in order to acting as a bulking agent (Martínez-Blanco et al., 2010), generating porosity and promoting liquid retention. This facility used the most typical technology for indoor plant composting in Spain, including in-vessel decomposition and a curing phase in turned windrows (Martínez-Blanco et al., 2011). The quality of the compost, including its microbiological and chemical safety (Table 1) met required standards (Quirós et al., 2015).

The fertilizer doses in each treatment were calculated considering all possible sources of N, including the mineral nitrogen (N) initially contained in the soil (Table 2) and the N addition during the study (Table 3). The sampling for determining the initial soil moisture and N content in each plot, prior to the study, was done at planting time at three different points and three soil depth intervals (0–20, 20–40 and 40–60 cm). Soil moisture content was determined gravimetrically, after drying triplicate samples at 105°C for 48 h. The soil extractable mineral N (NH_4^+-N, NO_3^--N, NO_2^--N), prior to the study, was determined following the method ISO 14256-2 (International Organization for Standardization, 2005),

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Table 1. Chemical and microbiological information on the compost used in the previous and current seasons of the study (no replicates of analysis, only for estimation purposes).

Property	Compost of the previous season	Compost of the current season
Moisture ($g\ kg^{-1}$ dry weight)	672	667
Organic matter ($g\ kg^{-1}$ dry weight)	560	500
pH (1:5 extract)	8.6	8.2
Total N ($g\ kg^{-1}$ dry weight)	26	18
Organic N ($g\ kg^{-1}$ dry weight)	25	14
C/N ratio	11	10
Heavy metals content	Class A	Class A
Escherichia coli (CFU/g)	<9	<9

Table 2. Soil moisture and extractable mineral N prior to the study (mean values ± standard deviation; $n = 3$).

Fertilization	Soil depth (cm)	Moisture content ($g\cdot kg^{-1}$)	Soil N ($kg\ N\cdot ha^{-1}$)[1]	Total soil N (0–60 cm) ($kg\ N\cdot ha^{-1}$)
C	0–20	236.7 ± 45.4	16.4 ± 3.8	36.0 ± 2.9
	20–40	163.4 ± 27.1	12.1 ± 1.7	
	40–60	145.6 ± 29.8	7.5 ± 1.2	
C + M	0–20	262.4 ± 48.4	14.8 ± 2.4	35.0 ± 3.1
	20–40	176.9 ± 27.7	12.2 ± 3.0	
	40–60	215.7 ± 45.1	8.0 ± 1.6	
M	0–20	196.4 ± 41.0	12.9 ± 3.2	31.0 ± 3.0
	20–40	149.4 ± 10.1	11.2 ± 2.1	
	40–60	160.7 ± 44.3	6.9 ± 1.1	

[1] Average (NH_4^+-N, NO_3^--N, NO_2^--N) of three samples and three N measurements per sample.

by extraction with potassium chloride solution, and compost N was estimated following the Kjeldahl method (Bremner, 1960). The soil bulk density was determined in order to express data as kg ha^{-1}. For the first layer (0–20 cm), the bulk density was measured from undisturbed soil core samples. For the deeper layers, the bulk density was calculated from a pedotransfer function (Saxton et al., 1986) (Table 2).

Concerning the mineral N inputs during the study (Table 3), NO_3^-N concentrations in the irrigation water were determined by the copperized Cd reduction colorimetric method described by Keeney and Nelson (1982). All treatments were provided with 50 kg ha^{-1} of mineral N, including C and C + M, due to the presence of mineral N in the irrigation water obtained from local wells. The amount of mineral N from fertilizer was calculated from its formulation. The estimated N inputs are given in Table 3. No replicates for this calculation could be performed.

Table 3. Estimated N inputs[1] to the fertilization treatments (kg $N\cdot ha^{-1}$).

Fertilization	Mineral N applied[2]	Compost N applied[3]	Total N[4]
C	50	114	200
C + M	140	56	231
M	230	0	261

[1] Theoretical values, partially calculated from the fertilizer formulation and dose (mineral N applied), and the predicted rate of mineralization from the compost of the previous season (compost N applied). No replicates can arise from such estimations; therefore, these data must only be interpreted for estimation purposes.
[2] Includes N from irrigation water (50 kg ha^{-1} in all treatments) and mineral fertilizer (KNO_3).
[3] N input from compost applied in the current and previous seasons.
[4] The estimated total N is the addition of the total soil N content at 0–60 cm prior to the study (Table 2) and the mineral and compost N inputs.

The use of compost during previous growing seasons in the C and C + M parcels was an additional source of available N, due to the slow mineralization of the compost N forms (Amlinger et al., 2003; Hargreaves et al., 2008). According to these authors, the additional contribution in the C and C + M treatments could be estimated as 12% of the N not mineralized in the previous season of application. Hence, the total N contribution was estimated to be 114 and 56 kg $N\cdot ha^{-1}$ in the C and C + M treatments, respectively. No replicates for this estimation could be performed (Table 3). Organic fertilizers can be supplied in accordance with the legal limit for N application, which is 170 kg N ha^{-1} in the UE (Council of the European Union, 1991).

Production and harvest quality

Ripe tomatoes (red stage) were harvested at three different times, which were determined according to when there were a significant number of ripe tomatoes. For production measurements, only central plants were considered, discarding the plants situated at the edges of the blocks. Crop yield was assessed by the total weight of the harvested fruit (total crop yield) and the weight of the marketable fruit (commercial crop yield). The individual weight, diameter and °Brix (Digital refractometer PR-32α, Atago, Tokyo, Japan) of 10 fruits per repetition were measured as quality parameters.

Extraction of phenolic compounds

One fruit per block was collected for the analysis of phenolic compounds, giving nine samples per treatment. The

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Table 4. Quality parameters and crop yield measured in tomato (varietal type 'Penjar') following compost (C), compost and mineral (C + M) and mineral (M) fertilization treatments.

	Fruit quality			Crop yield	
Fertilization	**Individual fruit weight (g)**	**Fruit diameter (mm)**	**° Brix**	**Total crop yield (kg·m^{-2})**	**Commercial crop yield (kg·m^{-2})**
C	63.9 *n.s.*	54 *n.s.*	6.2 *n.s.*	3.3 b	2.4 b
C + M	65.7 *n.s.*	54 *n.s.*	5.6 *n.s.*	6.0 a	4.6 a
M	64.0 *n.s*	56 *n.s.*	5.8 *n.s.*	5.8 a	4.2 a

Different small letters: significant difference between treatments; *n.s.*, no significant difference (P<0.05).

extraction procedure was performed according to the method described by Ribas-Agustí et al. (2012).

Total polyphenol content

Total polyphenols were assessed by spectrophotometry according to the method published by Singleton and Rossi (1965) with minor modifications. The methanolic extract (1 mL) was mixed with 3 mL ultrapure water (Millipore, Madrid, Spain) and 0.25 mL of 2 M Folin-Ciocalteu's reagent (Sigma-Aldrich, Madrid, Spain). After 1 min incubation, the reaction was stopped by adding 2.5 mL of 2.08 M Na_2CO_3 solution and 3.25 mL ultrapure water. After 2 h at room temperature, the absorbance of the sample was measured at 725 nm (UV-240 Graphicord, Shimadzu, Kyoto, Japan). Total polyphenols, expressed as caffeic acid equivalents, were calculated according to an external calibration curve of caffeic acid standard (Sigma-Aldrich, Madrid, Spain).

Analysis of phenolic compounds

Phenolic compounds were analyzed by UHPLC-DAD-MS/MS according to the method of Ribas-Agustí et al. (2012). Phenolic compounds were identified on the basis of their chromatographic retention time, UV-visible spectra and MS/MS spectra, matching with the commercial standards (5-caffeoylquinic acid and quercetin-3-*O*-rutinoside from Sigma-Aldrich, Madrid, Spain; kaempferol-3-*O*-rutinoside from Extrasynthèse, Genay, France). Other phenolic compounds were tentatively identified by comparing chromatographic retention time, UV-Visible spectra and MS/MS spectra with literature information (Gómez-Romero et al., 2010; Vallverdú-Queralt et al., 2011; Ribas-Agustí et al., 2012). Quantification was performed using diode array detection at $\lambda = 323$ nm for hydroxycinnamic acid derivatives and $\lambda = 350$ nm for flavonoids (quercetin and kaempferol derivatives). Compounds with no commercial standard available were quantified as equivalents of the standards with the most similar UV-VIS absorption properties (5-caffeoylquinic acid, quercetin-3-*O*-rutinoside, kaempferol-3-*O*-rutinoside).

Statistics

Tomato quality and crop yield, as well as phenolic compounds and total polyphenol contents were analyzed by one-way analysis of variance (ANOVA). *Post-hoc* differences between groups were further determined using the Tukey (HSD) test. In all instances, a significance level (α) was set at 0.05. SPSS software was used for all analyses (IBM, Armonk, NY).

Results and Discussion

Effect of MSW compost fertilization on tomato yield

The use of compost alone (C) had a detrimental effect on crop yield as compared with the use of mineral fertilizer (M) or the combination of compost and mineral fertilizers (C + M) (Table 4). The C treatment had 43% lower total and commercial crop yields than the M treatment. Similarly, C had 45 and 48% lower total and commercial crop yields, respectively, than C + M treatment. However, no significant differences in crop yield parameters were observed between the C + M and M treatments (Table 4).

Previous studies testing compost from different origins with and without mineral fertilization have reported contradictory results, with some studies demonstrating similar production rates (Clark et al., 1999; Martínez-Blanco et al., 2009; Martínez-Blanco et al., 2011), and others demonstrating significant decreases under compost conditions (Ghorbani et al., 2008; Riahi et al., 2009). It is generally assumed that N assimilation under mineral fertilization is direct and rapid, allowing regular production yields, while the dynamics of N mineralization from compost or other organic sources are more irregular and unpredictable (Clark et al., 1999). Due to the high complexity of factors affecting quality and crop yield, care is called for when comparing studies conducted under different agronomic conditions, and the results must be interpreted within the context of the study. In the case of the present study, we need to consider that the fertilizer doses in all three treatments followed the regular recommendations for intensive tomato cultivation

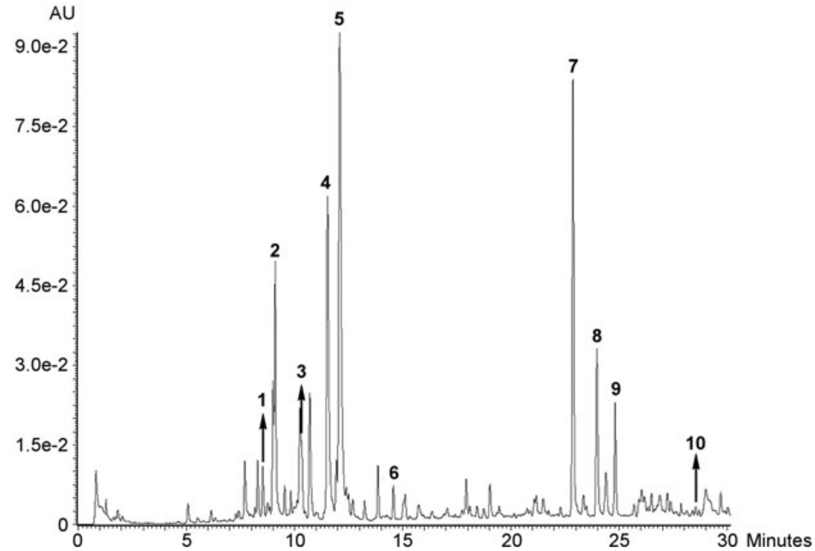

Figure 1. HPLC-DAD chromatogram showing the identified phenolic compounds in *Solanum lycopersicum* L., varietal type 'Penjar', λ = 350 nm. Identification of peaks: 1, coumaroyl-hexose; 2, caffeoyl-hexose I; 3, caffeoyl-hexose II; 4, 4-caffeoylquinic acid; 5, 5-caffeoylquinic acid; 6, quercetin-rutinoside-hexoside; 7, quercetin-rutinoside-pentoside; 8, quercetin-3-*O*-rutinoside; 9, kaempferol-rutinoside-pentoside; 10, tricaffeoylquinic acid.

and for compost fertilization in this region (Martínez-Blanco et al., 2013), which probably contributed to the differences estimated among treatments for the input of N (Table 3). Such differences may explain some of the production differences obtained between the C treatment and the other test groups. On the other hand, fertilizer responses were evaluated for a coarse-textured soil with low organic matter content, which would have seriously limited soil N supplying power and thereby enhanced the need for fertilizer N. The yield limitation observed with the C treatment may not have occurred with a soil better able to supply N through mineralization. In addition, it has been demonstrated that an increased yield can be expected in crops after 4–5 years of organic management due to physical, chemical and biological soil improvement (Creamer et al., 1996; Colla et al., 2002). The historical compost use of the C treatment parcel originated three years before the current study. Hereto, higher production yields might be expected in the future if compost fertilization is an ongoing practice.

Effect of MSW compost fertilization on tomato fruit quality

The use of compost, alone (C) or combined with mineral fertilizer (C + M), did not affect quality parameters (fruit weight, diameter and °Brix) of 'Penjar' tomato in comparison with what was obtained with mineral fertilization (M) (Table 4). These results are in accordance with those of Riahi et al. (2009) and Martínez-Blanco et al. (2011), who found no quality differences in other tomato varieties grown under compost and conventional systems.

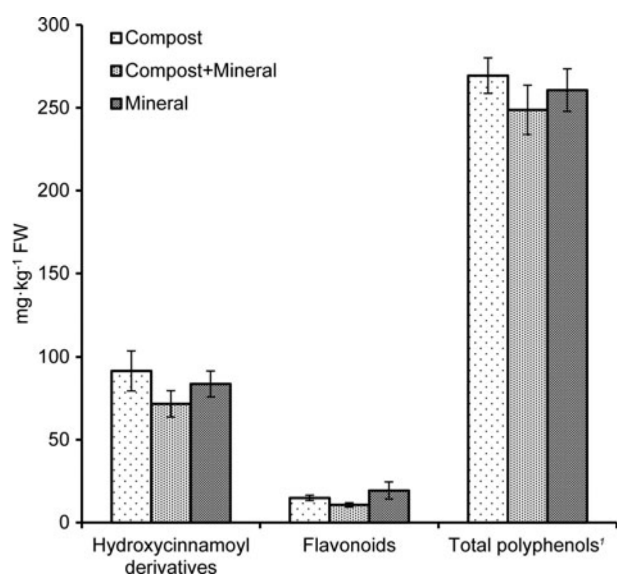

Figure 2. Total hydroxycinnamoyl derivatives and flavonoids (as measured by HPLC), total polyphenols (as measured by Folin Ciocalteu's method) and effect of fertilization treatment in tomato var. 'Penjar'. Bars represent the average of $n = 9$ and error bars show standard error of the mean. [1]mg·kg^{-1} caffeic acid equivalents, fresh weight.

Phenolic content in 'Penjar' tomato as affected by MSW compost fertilization

A chromatogram of the main phenolic compounds of '*Penjar*' tomato is shown in Figure 1. Quercetin-3-*O*-rutinoside (rutin) and 5-caffeoylquinic acid (chlorogenic

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Table 5. Phenolic content (mg·kg^{-1} fresh weight±standard error of the mean) in tomato (varietal type 'Penjar') after different fertilization treatments: compost (C), compost and mineral (C + M) and mineral (M).

Phenolic compounds	Fertilization			*P*
	C	C + M	M	
Coumaroyl-hexose[1]	35.8 ± 5.8	25.4 ± 3.8	22.2 ± 1.8	0.081
Caffeoyl-hexose I[1]	16.5 ± 2.3	12.8 ± 1.3	12.9 ± 0.9	0.224
Caffeoyl-hexose II[1]	3.9 ± 0.3	3.2 ± 0.3	3.7 ± 0.4	0.357
4-Caffeoylquinic acid[1]	10.9 ± 1.0	8.9 ± 0.7	11.4 ± 1.0	0.137
5-Caffeoylquinic acid	21.8 ± 3.5	19.1 ± 2.6	31.0 ± 5.1	0.105
Tricaffeoylquinic acid[1]	2.6 ± 0.3	2.2 ± 0.2	2.5 ± 0.1	0.432
Quercetin-rutinoside-hexoside[2]	0.8 ± 0.1	0.9 ± 0.1	1.1 ± 0.2	0.365
Quercetin-rutinoside-pentoside[2]	7.1 ± 0.8	4.4 ± 0.5	9.0 ± 2.5	0.134
Quercetin-3-*O*-rutinoside	5.5 ± 0.9	4.5 ± 0.8	8.5 ± 2.5	0.221
Kaempferol-rutinoside-pentoside[3]	1.5 ± 0.2 a	1.0 ± 0.1 b	0.8 ± 0.2 b	0.008

[1] Quantified as 5-caffeoylquinic equivalents.
[2] Quantified as quercetin-3-*O*-rutinoside equivalents.
[3] Quantified as kaempferol-3-*O*-rutinoside equivalents.
The effect of the treatment is expressed with the one-way ANOVA *P*-value. Different letters within a row indicate significant differences after *post-hoc* testing (α = 0.05).

acid) were identified on the basis of their matching with commercial standards. Eight other major phenolic compounds were tentatively identified in 'Penjar' tomato (as described in the section 'Methods') according to data from Gómez-Romero et al. (2010), Vallverdú-Queralt et al. (2011) and Ribas-Agustí et al. (2012). From these, five hydroxycinnamic acid derivatives were quantified as 5-caffeoylquinic acid equivalents: two isomeric forms of caffeoyl-hexose (I and II), coumaroyl-hexose, 4-caffeoylquinic acid and tricaffeoylquinic acid. In addition, two quercetin derivatives were quantified as equivalents of quercetin-3-*O*-rutinoside: quercetin-rutinoside-hexoside and quercetin-rutinoside-pentoside. A kaempferol derivative was quantified as equivalents of kaempferol-3-*O*-rutinoside: kaempferol-rutinoside-pentoside. Compounds within the group of caffeoylquinic acid derivatives constituted the majority of the phenolic content in 'Penjar' tomatoes, although significant levels of flavonoids were also present (Fig. 2).

It has been reported that 'Penjar' tomatoes accumulate high levels of total polyphenols (Cortés-Olmos et al., 2014; Figàs et al., 2015). However, this work profiles for the first time the individual phenolic compounds of this varietal type. The phenolic profile in tomato fruit depends strongly on the variety (Slimestad and Verheul, 2009; Ribas-Agustí et al., 2012). In this sense, a remarkable trait of the 'Penjar' tomato investigated in this study was the absence of the phenolic intermediate naringenin chalcone, which is on the contrary accumulated in significant amounts in other tomato varieties (Ribas-Agustí et al., 2012, 2013; Erba et al., 2013).

MSW compost fertilization resulted in subtle differences in the phenolic content of 'Penjar' tomato, namely in the case of the flavonoid kaempferol-rutinoside-pentoside, whose content was significantly higher in compost-fertilized 'Penjar' tomatoes (Table 5). The rest of the hydroxycinnamic acid derivatives and flavonoids did not change significantly, regardless of the fertilization treatment. No significant differences were observed in the sum of hydroxycinnamic acids, flavonoids or in total polyphenols between the three fertilization strategies (Fig. 2).

As in the evaluation of the crop yield, special attention needs to be paid when comparing different studies, due to the potential confounding effect of uncontrolled factors. It has been suggested that lower N availability, which would be expected with compost fertilization, is likely to produce such a plant stress as to induce phenolic compound synthesis in order to better protect against disease (Brandt and Mølgaard, 2001). For example, the significant increase in the accumulation of kaempferol-rutinoside-pentoside in 'Penjar' tomato under MSW compost fertilization is likely due to reduced N availability. However, if the whole phenolic content is taken into account (Table 5), the fertilization regime had no effect on the total phenolic content under the assayed conditions. The results presented herein are consistent with those of other authors who also tested compost fertilization for affecting tomato phenolic content (Riahi et al., 2009). Some groups have reported clearer positive effects of organic management, including compost fertilization, on tomato phenolic content (Caris-Veyrat et al., 2004; Mitchell et al., 2007). In these cases, we need to consider that agronomic practices other than fertilization may induce additional plant stress and have an additive effect on tomato phenolic content (Rosales et al., 2011).

Conclusions

In major urban areas such as Barcelona, which borders an important agricultural zone, the generation and use of composted MSW as fertilizer provides a particularly attractive opportunity. However, the use of composted MSW needs to be supported with studies regarding the possible effect on crop yield and quality. The aim of this study was to find a viable way to minimize urban waste while maximizing the reutilization potential of this nutrient-rich source. This work demonstrated that similar tomato production and quality values (i.e., fruit weight, diameter, °Brix and phenolic content) can be achieved by partially replacing mineral N fertilizer with composted MSW, as compared with mineral fertilization only.

The present study was focused on the agronomic effects of fertilizing with MSW compost. It would be of special relevance to perform future studies on its environmental implications, in order to have a comprehensive evaluation of using MSW compost in those fertilization programs aiming to be sustainable.

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Conflict of interest

The authors have no conflicts of interest to disclose.

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