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Does the timing of short-term biowaste compost application affect crop growth and potential nitrate leaching? The case studies of processing tomato and cauliflower under field conditions

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Highlights

- *Biowaste compost decreased the aboveground biomass accumulation and yield in processing tomato and cauliflower.*
- *Biowaste compost alone did not meet the N requirement in processing tomato and cauliflower.*
- *Biowaste compost distribution in the summer before the processing tomato growing season alleviated its depressive effect in reducing DM and yield.*
- *Biowaste compost distribution in the spring before the cauliflower growing season alleviated its depressive effect in reducing DM and yield.*
- *Biowaste compost decreased the N-NO_3 concentration in soil solution compared to mineral fertilisation with a positive effect in reducing N leaching risks in the groundwater.*

Abstract

The feasibility of municipal solid waste compost (MSWC) as a substitute for mineral nitrogen (N) fertiliser was tested for a spring-summer (*i.e.*, processing tomato) and an autumn-winter (*i.e.*, cauliflower) vegetable crop grown in Mediterranean open field conditions. Two different doses (10 and 20 t dm C ha^{-1}) and two distribution timings for each dose (*i.e.*, early application at about nine months before processing tomato transplanting and five months before cauliflower transplanting: C10_early and C20_early; late application at about one month before processing tomato and cauliflower transplanting: C10_late and C20_late) were compared in a two-year field experiment. An unfertilised control and a 100% mineral N fertilisation (MIN, 200 kg N ha^{-1} for processing tomato and 150 kg N ha^{-1} for cauliflower) were added to the experiment. The application of MSWC significantly reduced the aboveground DM accumulation compared to the MIN in both crops, and it was inadequate to ensure a high yield for spring-summer and autumn-winter vegetables. However, the timing of compost application seems to play an essential role in reducing the reduction of crop growth due to compost application. In both tomato and cauliflower, when the MSWC was applied a few months earlier than the transplanting (*i.e.*, in the previous summer in tomato and the previous spring in cauliflower), the DM and yield reduction was less apparent than in soil where compost was applied immediately before transplanting. Despite the lowest N-uptake associated with the MSWC application, the N-NO_3 concentration in the soil solution was reduced by MSWC. In addition to the amendment effect, compost use may positively impact lowering N leaching risks in the groundwater. Combining the use of MSWC applied early before the crop season with mineral N fertiliser, it is possible to gain high yield, increase soil organic carbon and reduce groundwater contamination risk both in spring-summer and autumn-winter vegetable crops.

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Introduction

Optimal nitrogen management represents a key factor for the sustainability of agroecosystems, especially if vegetable crops are included (Thompson *et al.*, 2017; Bruuslema, 2018; Tei *et al.*, 2020). Indeed, it is well known that several vegetable crop species have a relatively low nutrient use efficiency compared to arable crops, often related to the short crop cycle, superficial rooting, relatively high N demand, and short rotation (Cameira and Mota, 2017; De Rosa *et al*., 2017; Tei *et al*., 2020). On the other hand, excessive use of mineral fertilisers has led to issues like nutrient run-off, N leaching, decreased stable soil organic matter and microbial activity (Hernandez *et al*., 2014; Latini *et al.,* 2021). In the Mediterranean environment, the losses of organic matter are increased by specific weather conditions (Zaccardelli *et al.,* 2021). In this context applying organic matter to the soil is a suitable practice for mitigating soil degradation while reducing environmental pollution caused by improper mineral fertilisation management (Diacono and Montemurro, 2010; Garcia *et al*., 2017; Mauceri *et al*., 2020). Amendments (*i.e*., compost, poultry manure, peat, sewage sludge, or others) increase soil organic matter and nutrient availability, enhance soil structure, porosity, structural stability, water penetration, and protect soil from erosion (Hernandez *et al*., 2014, Sambo and Nicoletto, 2017). Moreover, amendments rich in humic substances release nutrients gradually with a protracted effect on plants and edaphic microorganisms (Chaparro *et al*., 2014). Among these amendments, the use of municipal solid waste compost (MSWC) as a soil conditioner and fertiliser represents one of the best means for maintaining and restoring soil productivity due to the capability of sequestrating C and increasing the soil organic matter content while contributing to mitigate the greenhouse effect (Giannakis *et al.,* 2014, Garcia *et al*., 2017; Diacono *et al*., 2019; Sharma *et al*., 2019). In addition to the agronomic value of compost, its use in agriculture is also attractive for the recovery of organic biomasses, and its distribution into the soil could help close the organic fraction circle of municipal organic wastes (Horrocks *et al.,* 2016; Martinez-Blanco *et al*., 2011; Moretti *et al*., 2020). The creation of a circular economy is also strongly endorsed by the European Commission (EC-Closing the Loop, 2015; EC-Update Bioeconomy strategy, 2018). The search for solutions to recycling the organic fraction of municipal wastes is also imposed by the increased amount of waste produced by municipalities with the door-to-door collection system of refuses (Brunetti *et al*., 2019). In Italy, 505 kg of municipal waste per capita were generated in 2020, for a total of 220 million tons in the European Union (EUROSTAT, 2021), and environmental agencies have increasingly promoted its use in agriculture. Compost distribution in the soil provides substantial environmental and economic advantages in contrast to traditional biosolids' management practices, such as combustion and landfill disposal or incineration (Giannakis *et al*., 2014; Sharma *et al*., 2019).

Considering agronomic performance related to the use of compost, a wide range of results have underlined the great potential for compost as a nutrient source (mainly N) to assure adequate yield and an increase in quality traits (*i.e*., antioxidants, vitamins, protein content, *etc*.). However, the fate of the nitrogen depends primarily on the composition and maturity of the compost, as well as climatic conditions and management practices (Martinez-Blanco *et al*., 2014; De Rosa *et al*., 2017). Many studies indicate that compost may reduce crop growth and yield when applied alone, especially in the case of immature compost, due to immobilisation of native or added available N (Giannakis *et al*., 2014; Moretti *et al*., 2020). Martínez-Blanco *et al.* (2011) reported that, on average, between 5 and 22% of the nitrogen in compost is available during the first year, and 40-50% is available in the 3rd -5th years. Repeated applications can partially counteract the early reduction in N availability, as they contribute to efficient microbial degradation and mineralisation communities and build an organic stock of nutrients (García-Gil *et al*., 2000; Diacono and Montemurro, 2010; Moretti *et al*., 2020). The combination of compost and N mineral fertilisers improves early N availability for crops by being present in readily-available forms and stimulating the soil microbial community by adding mineral N (Morra *et al.,* 2013; 2021). Islam *et al*. (2017) reported an increase in yield in tomatoes when vermicompost was used as a complement of mineral fertilisers.

Similarly, Hernandez *et al*. (2014) found that by combining compost and mineral fertiliser, tomato yield and fruit quality were similar to the solely inorganic fertigated control, while some biochemical soil parameters were increased. A comparable result was also recorded by Nicoletto *et al.* (2013) in cabbage after applying compost alone or in combination with mineral fertilisation. Another possible solution to increase the amount of N available for the crop and limit the suppressive effect due to the N immobilisation soon after the land application could be through earlier application relative to the time of sowing or transplanting and the subsequent crop N-uptake. Hargreaves *et al.* (2008) reported that 16-21% of the total N in compost was available as NH_4NO_3 six months after application. However, the effect of compost application timing into the soil, and its interaction with the dose has not been robustly investigated so far.

Moreover, few studies investigated the effect of compost in reducing N leaching risks into groundwater. Thus, this research aimed to evaluate the effect of different compost application timing and doses on crop growth and yield and the potential N leaching in summer and autumn vegetable crops in central Italy. Our hypothesis was that: i) the amount of N available for crop uptake depends on both the dose and timing of compost distribution into the soil; ii) the effect of the timing of compost application may also depend on the season when crops are growing (*i.e*., spring, summer, *etc*.), and; iii) apart from the effect on yield, the use of compost may help to maintain a low nitrate concentration in the soil solution thus limiting risks of nitrate load.

Materials and methods

Experimental site, treatments, and crop management

Field experiments were conducted at the Experimental Station of the Department of Agricultural, Food and Environmental Sciences, the University of Perugia, located in the middle of the Tiber plain (Central Italy, 42.96°N, 12.37°E, 165 m a.s.l.). Tomato and cauliflower were produced during two growing seasons (2014 and 2015 for tomato, 2013 and 2015 for cauliflower). The crops were chosen to evaluate the effects of MSWC application in the different growing seasons: a spring-summer vegetable crop (*i.e*., *Solanum lycopersicum* L., cultivar Perfectpeel) and an autumn-winter vegetable crop (*i.e*., *Brassica oleracea var. botrytis*, L., cultivar Ravella). Processing tomato and cauliflower were also chosen to be two of the most representative vegetable crops for the Mediterranean environment. The compost used in this study was a commercial 1-year-old biowaste compost that originated from a mixture of municipal solid wastes and pruning residues (50/50, w/w), purchased from Gesenu (Perugia, Italy). The soil in the top 0.5 m was clay-loam (Fluventic Haplustept, Soil Taxonomy), composed of 44% silt, 25% sand, 32% clay, 1.3% organic matter (Walkley-Black method), with a total N of 0.96 g kg^{-1} (Kjeldahl method), high content of extractable P (25.4 mg kg^{-1}, Olsen method) and exchangeable K (254 mg kg^{-1}, ammonium-acetate method), and pH of 8.03 (in water).

Both crops were subjected to four experimental treatments, focusing on different doses and timing of application of MSWC, consisting of two doses (*i.e*., 10 and 20 t ha^{-1} as dry matter) and two-timing applications for each amount (*i.e*., early: C10_early and C20_early, where compost was applied about nine months and five months before the transplanting of processing tomato and cauliflower respectively; late: C10 _late and C20_late, where compost was applied about one month before the transplanting of both crops). In addition, two controls were also included where MSWC was not applied to the soil: mineral fertilised control (MIN) and unfertilised control (N0), for a total of 6 experimental treatments with three replicates arranged in a completely randomised block design. Plot size was 50 m^2 in both years and crops, and the second cycle was carried out in different plots of both processing tomato and cauliflower. In processing tomatoes, MSWC was incorporated in the soil at the end of August for the C10_early and C20_early and at the beginning of May for the C10_late and C20_late. In cauliflower, MSWC was incorporated in the soil at the end of March for the C10_early and C20_early and at the end of July in C10_late and C20_late. After the compost incorporation and before the crop transplanting, the soil was left bare without any mineral fertilisation to verify the effect of the solely MSWC amendment on the first crop grown. Considering the chemical characteristics of MSWC (Table 1), soil amended with the C10_early and C10_late received 180 kg N ha^{-1} and 2.5 t ha^{-1} of organic C, while the C20_early and C20_late received 360 kg N ha^{-1} and 5 t ha^{-1} of organic C. The MIN treatments consisted of 200 kg N ha^{-1} as liquid mineral fertiliser (7.5% NO_3-N, 7.5% N-NH_4, and 15% urea-N) applied through drip irrigation for processing tomato and 150 kg N ha^{-1} of ammonium-nitrate broadcast split into two doses (50 kg N ha^{-1} at transplanting and 100 kg N ha^{-1} one month later) for cauliflower. In all treatments, 100 kg P_2O_5 ha^{-1} and 100 kg K_2O ha^{-1} had been broadcast for all treatments at plowing. The same irrigation volume was applied in a twice-weekly irrigation schedule for all treatments and crops, according to the FAO method (Allen *et al.,* 1998). The reference crop for Kc assessment was the treatment with the greatest canopy (*i.e*., MIN) in each growing season and crop, as reported in Farneselli *et al*. (2015).

No pest control was necessary during the growing cycle, and weeds were controlled by hand-weeding.

The preceding crop was soft winter wheat in both vegetable crops and growing seasons.

Processing tomato was transplanted on 22nd May 2014 and 20th May 2015 at a density of 3.2 plants m^{-2} arranged as single rows 1 m apart. Cauliflower was transplanted on 8th August 2013 and 27th August 2015 at the density of 3 plants m^{-2} arranged as single rows 1 m apart.

Plant sampling

The aboveground dry matter (DM) of processing tomato at final harvest (carried out on 21st August 2014 and 18th August 2015, when about 80% of the fruits were ripe) was determined by sampling twenty plants per plot. Then vegetative parts were separated from the fruits, and further divided into marketable, unripe, and rotten fruits, to calculate total fruit yield (TY) and marketable fruit yield (MY). A sub-sample of twenty fruits for each treatment was then selected to determine the following parameters: mean weight, pH of the tomato juice, and solid soluble content (°Brix).

The DM of cauliflower at the maturity stage (carried out on 29th October 2013 and 30th November 2015) was determined by sampling eight plants per plot that were randomly selected, then separating vegetative parts from the curd. Yield parameters were recorded as total curd fresh weight, one curd fresh weight, and curd diameter.

Both processing tomato and cauliflower biomass samples were oven-dried at 80°C, ground to a fine powder, and subjected to Kjeldahl digestion and analysis of the reduced N concentration, as employed by Farneselli *et al.* (2020). Nitrogen accumulation in processing tomato and cauliflower biomass was calculated as the product of total biomass by reduced-N concentration.

NO_3-N concentration in soil solution below 0.9 m depth

In both years and crops, lysimeters (SDEC, France) consisting of porous ceramic cups (32 mm external diameter by 95 mm length) were installed at 0.9 m depth in each plot. Samples of the soil solution were taken using a portable vacuum pump. The water samples' nitrate-nitrogen (NO_3-N) concentration was measured with an ion-specific electrode meter (Spectrum Technologies Inc., USA), as described by Farneselli *et al*. (2020). Water samples were collected about 12 hrs after each irrigation or fertigation event, both in the processing tomato and cauliflower cycle and after each heavy rain event. According to the method proposed by Gabriel *et al*. (2012), the NO_3-N concentration was used to assess the potential risks for N leaching with drainage water.

Data analysis

The whole dataset (two years and two crops) was analysed by ANOVA, using a mixed model, with year, treatment type, and 'year by treatment' interaction as fixed effects and blocks within years as a random effect. Before analysis, all data were checked for normality and homogeneity of the variance. Then, means were compared using the generalised multiple comparison procedure suggested by Hothorn *et al.* (2008) and a single-step multiplicity adjustment. Finally, statistical analysis of the data was performed using the R statistical environment.

Results

Weather conditions

Rainfall and temperature regimes during each experimental year of the two crops are reported in Figure 1.

For processing tomatoes (May-August 2014 and May-August 2015), the first year was very wet, with 280 mm of total rainfall in the whole growing season, while the second year was much drier, with only 180 mm of rain in total, in line with the 30-year average. The two years were also different for the rainfall recorded in the autumn-winter period that preceded the crop cycles. Indeed, in the first year (*i.e*., September 2013-March 2014), total rainfall (700 mm) was more significant than in the following year (*i.e*., September 2014-March 2015, 600 mm, data not shown). The thermal regime in the processing tomato growing season was also quite different between the two years: 2014 was in line with the 30-years average, while 2015 was warmer than the first year.

As far as the cauliflower growing season is concerned (*i.e*., from August to October in 2013 and from August to November in 2015), in the first year, total rainfall was in line with the 30-year average (210 mm), while in the second year it was much higher (*i.e*., 208 mm) (Figure 1). During the two cauliflower growing seasons, temperatures were slightly higher than the 30-year average in both years (Figure 1).

Aboveground dry matter and nitrogen accumulation and fruit yield in processing tomato

The aboveground DM of processing tomato at final harvest was significantly affected by timing and dose of MSWC application in both years (Table 2). In 2014 DM was higher than in 2015 in the C10_early and C20_early and in the MIN (+28% as an overall average), while in the other treatments, DM was similar in both years. The late application of MSWC decreased the DM accumulation compared to the mineral fertilized treatments (–56% in 2014 and –38% in 2015, C_late vs. MIN, as an average over the two doses) and determined DM values similar to those of the unfertilised control. The early distribution of MSWC also decreased the aboveground biomass concerning the MIN, but the gap was lower than in the late treatments (–28% in 2014 and –31% in 2015 in C_early *vs* MIN, as an average over the two doses). Moreover, in C_early treatments, DM was higher than in C_late, but the effect varied with the MSWC dose and year. In detail, in 2014, DM in C_early was 96% and 62% higher than in C_late application at the 20 t ha^{-1} and 10 t ha^{-1} dose, respectively, while in 2015, the increase of DM was statistically significant only for C20_early compared to C20_late (+30%). The amount of MSWC application slightly affected the crop response in the early distribution at the highest dose in 2014, when DM in C20_early was about 20% higher than in C10_early, while it had no significant effect on the late treatments in both years.

The amount of N-uptake at the maturity stage was highest in MIN, and it was decreased by MSWC application according to the trend observed for the DM (Table 2). The reduction caused by MSWC late application compared to MIN treatments was about –70% in 2014 and –55% in 2015 as an average over the two doses. In the C_early, the reduction was minor than in C_late, and it was about –50% as an average over the two years and doses. Considering the aboveground DM, the total and marketable fruit yields were reduced by MSWC application, and the reduction was higher in the case of late application in both years (Table 2). The differences among treatments for TY and MY were in line with those described for the aboveground DM, although the gap between TY and MY of MSWC and MIN treatments was the highest (–56% and –40% in C_late and C_early *vs* MIN, respectively, as an average over the two doses).

None of the treatments had significant effects on marketable fruit quality in both years: the average pH was 4.4 (standard error of the difference, SED 0.029), and the average °Brix was 4.3 (SED 0.17) (data not shown).

N-NO_3 concentration in soil solution during the processing tomato growing season

The N-NO_3 concentration in the soil solution (Figure 2) during the processing tomato crop cycle was significantly higher in MIN than in any other treatments starting from 40 days after transplanting (DAT) in 2014 and from 50 DAT in 2015. Among MSWC treatments, differences did not appear relevant, except for the lowest concentration measured in N0 and C10_late between 30 and 50 DAT in 2014.

Table 1. Main properties of the biowaste compost used in the experiments. Values are referred to dry matter.

Parameters	Value
pH	8.5
Moisture (%)	13.3
Total organic carbon (%)	25.2
Humic + Fulvic acids (%)	11.9
Total N (%)	1.8 (1.73 org + 0.07 min)
Organic matter (%)	43.3
C/N	9.4

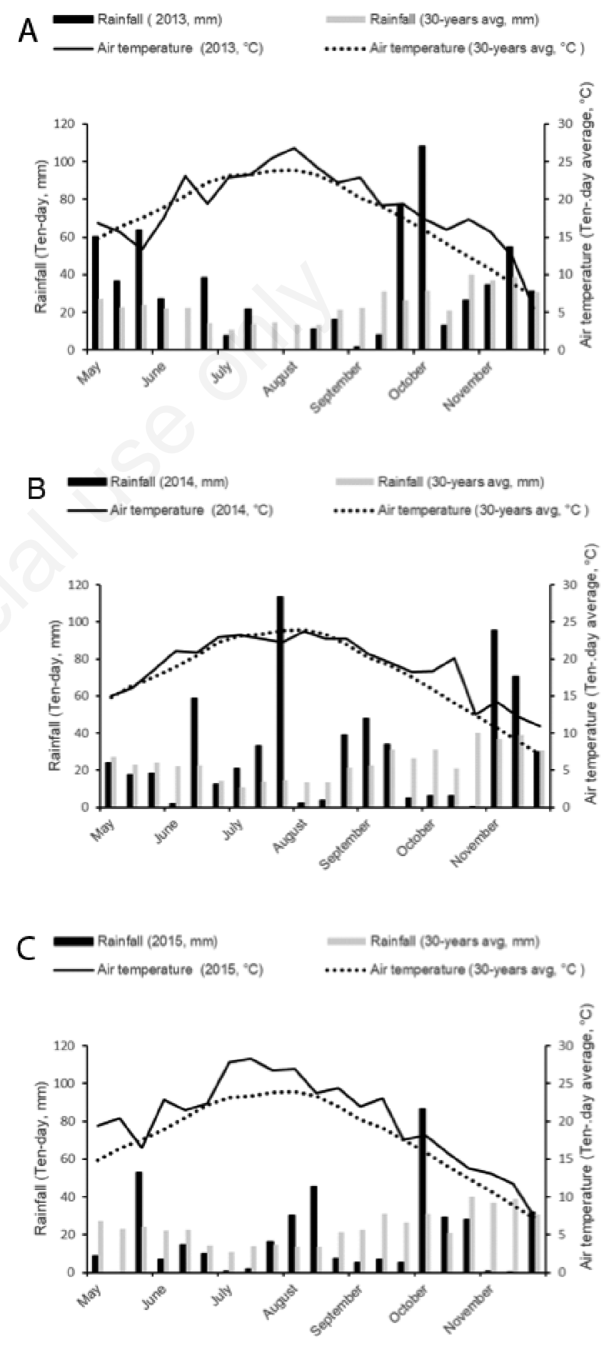

Figure 1. Ten-day mean rainfall (black vertical bar) and ten-day mean air temperature (continuous line) during the periods May-November 2013 (A), May-November 2014 (B), and May-November 2015 (C) compared to the ten-day rainfall (grey vertical bar) and ten-day mean air temperature (dashed line) as a 30-year average.

Aboveground dry matter and nitrogen accumulation and yield in cauliflower

The aboveground DM accumulation in cauliflower at the maturity stage was significantly affected by treatment and year (Table 3). In 2013 DM was higher than in 2015 in all treatments (+26% as an overall average) except for MIN, which showed similar values in both years. The early MSWC application at both doses in 2013 resulted in DM accumulation similar to that measured in MIN, while in 2015, DM in C_early was 24% lower than in MIN. The late MSWC application caused the highest reduction of DM in both years (–30% C_late *vs* MIN in 2013 and –56% C_late *vs* MIN in 2015, as an average over the two doses).

The accumulation of N-uptake at the harvest was higher in 2013 than in 2015 (+32% as an overall average) in all treatments except in the MIN control, which showed similar values in both years, according to DM (Table 3). The MSWC application caused a substantial reduction of N-uptake, especially in the case of late treatments, while the dose within each timing had no effect. In detail, N-uptake was 70% in C_late and 40% in C_early lower than in MIN, as the 2-year average.

According to DM, the curd yield in 2013 was higher than in 2015 (+44% as an overall average), except for the MIN control, which showed similar values in the two years (Table 3). Among MSWC treatments, the C_late caused the highest yield reduction compared to MIN (–48% in 2013 and –74% in 2015), while the curd yield in C_early was –15% and –40% lower than the MIN in 2013 and 2015, respectively.

The mean curd weight and diameter showed the same trend in curd yield in both years (Table 3).

N-NO_3 concentration in soil solution during the cauliflower growing season

The N-NO_3 concentration measured in the soil solution during the cauliflower crop cycle was significantly higher in 2015 than in 2013, especially at the beginning of the growing season when the values were more than double (Figure 3). In both years, differences among treatments did not appear relevant except for the consistently highest N-NO_3 concentration in MIN.

Discussion

Processing tomato and cauliflower yields recorded in this study associated with the mineral fertilisation were in line with the average values obtained in the same environment in conventional cropping systems (Nicoletto *et al.,* 2013; Farneselli *et al*., 2018; Tempesta *et al*., 2019). As expected, the application of MSWC significantly reduced the aboveground DM accumulation compared to MIN in both crops. The reduction was in a similar range to that

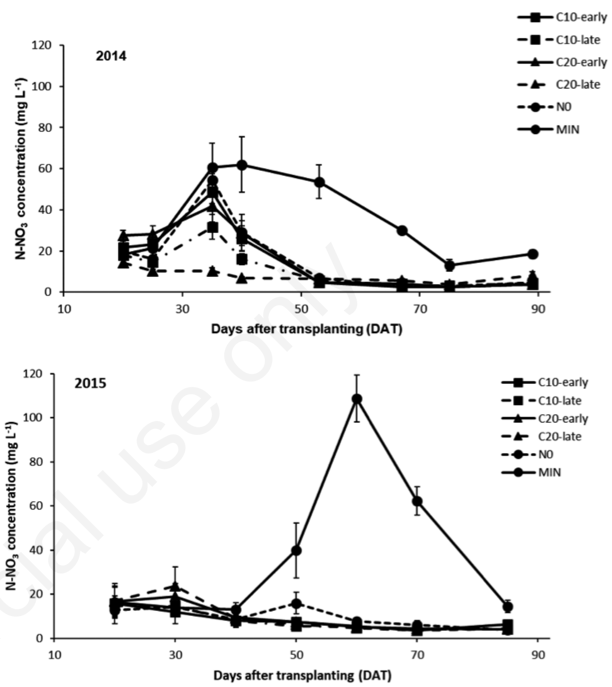

Figure 2. Time course of NO_3-N concentration in soil solution (mg L^{-1}) at a 0.9 m depth during the periods May-August 2014 (up) and May-August 2015 (down) in processing tomato grown with different timing (early and late) and doses (10 and 20 t dm ha^{-1}) of MSWC application. Vertical bars indicate ± standard error of means (3 replicates).

Table 2. Aboveground dry matter accumulation (DM), total N-uptake (N_{up}), total fresh fruit yield (TY), and marketable fresh fruit yield (MY) in processing tomato grown in 2014 and 2015 with different timing (early and late) and doses (10 and 20 t dm ha^{-1}) of MSWC application. Early application was at the end of August (*i.e.*, about nine months before transplanting); the late application was at the beginning of May (*i.e.*, about one month before transplanting).

Treatments	DM (Mg ha^{-1})		N_{up} (kg ha^{-1})		TY (Mg ha^{-1})		MY (Mg ha^{-1})	
	2014	2015	2014	2015	2014	2015	2014	2015
C10_early	7.31	5.56	107	129	66.6	55.8	55.8	43.8
C10_late	4.51	5.59	75	120	50.6	63.1	42.8	49.0
C20_early	8.85	5.93	130	127	69.6	75.9	56.6	61.8
C20_late	4.52	4.51	72	90	40.6	42.4	35.3	24.3
N0	5.20	5.66	69	126	46.4	70.4	37.0	59.0
MIN	11.2	8.29	281	237	122.9	102.4	94.6	77.3
Significance of fixed effects								
Treatment (T)	***		***		***		***	
Year (Y)	***		***		*		ns	
T × Y	***		***		**		***	
Pooled SED	0.252		3.11		2.51		3.33	

reported in several studies on summer cereal crops (Moretti *et al.*, 2019; Mauceri *et al.,* 2020), tomato (Hernandez *et al.,* 2014), and cauliflower (Quiros *et al.,* 2014). However, our results disagree with those of Zaccardelli *et al.* (2021), which found a comparable yield between a tomato grown in compost amended soil and a mineral fertilised soil. This apparent discrepancy could be explained by a higher dose (up to 30 t ha^{-1}) of compost applied in that study compared to the dose used in our study (10 or 20 t ha^{-1}). Similar to Zaccardelli *et al.* (2021), Shabani *et al.* (2011) reported a significant increase in yield using a high dose of compost in summer vegetables (the best rate was 50 t ha^{-1}). In addition, the environmental conditions of the cited previous researchers were warmer than those of our experiment and may have increased the mineralisation rate of the organic fraction of the compost applied.

The DM decrease associated with the MSWC treatments was probably due to the nutrient limitation, mainly N, in both crops. According to Antoniadis (2013), the N deficiency after MSWC may be attributed to the slow release of organically bound nutrients from the compost and to the N immobilisation by soil microorganisms. Consequently, due to this nutrient deficiency, the N-uptake at harvest in MSWC treatments was significantly lower than in the MIN treatments and, in some cases, lower than in N0. At the same time, the N concentration in the dry matter in fruits and residues showed the same trend among the thesis in both crops (data not shown). As expected, both crops reacted by reducing the final yield, supporting the suggestion that short-term application of compost cannot substitute mineral N fertilisation for both summer and autumn-winter vegetables at the low rates applied in our experiment (Martínez-Blanco *et al.,* 2011; Hernandez *et al.,* 2014; Quiros *et al.,* 2014). The N immobilisation due to compost application occurred even though the C:N ratio of our compost was meagre (10), contrary to the assumption that compost with low C:N generally increases soil N availability in the short-term (Hargreaves *et al*., 2008; Weber *et al*., 2014). However, it is worth noting that the agronomic response of a crop grown in an amended soil also depends on the type of compost. In our experiment, municipal solid waste compost was used, but its effect could be different from compost without pruning residues, although the two amendments could have similar C:N (Garcia *et al.,* 2017). Our results seem to support the hypothesis of Horrock *et al.* (2016), who assumed that the compost C:N ratio may be an inadequate predictor of N mineralisation potential. The pool of mineral N in the compost may more accurately predict N availability to the first crop after compost application, concerning its C:N. Based on this hypothesis, the amount of mineral N applied with compost and available for the two crops was very low (7 and 14 kg N ha^{-1} for the two doses respectively) and, it justifies the low crop N-uptake and N-use efficiency measured in the MSWC treatments.

In addition, our study suggests that the reduction of biomass and N accumulation related to MSWC application seems to be unaffected by the environmental conditions of the crop growing season. Indeed, unsatisfactory DM accumulation and fruit yields were obtained either in tomatoes with a typical spring-summer

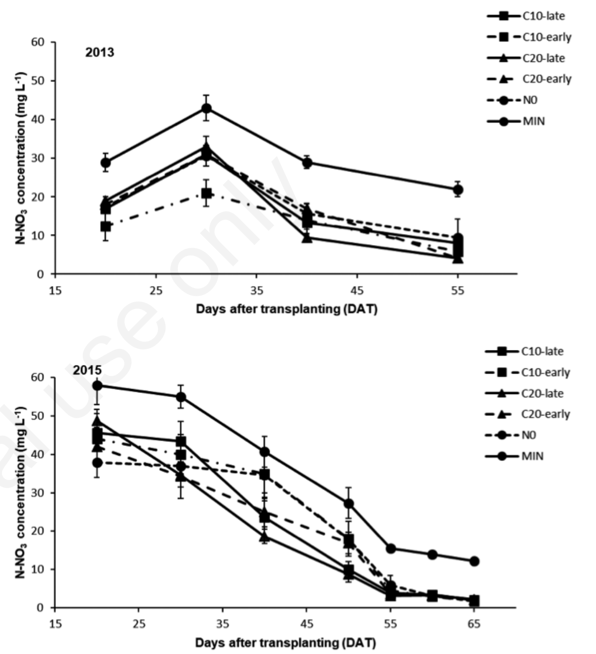

Figure 3. Time course of NO_3-N concentration in soil solution (mg L^{-1}) at a 0.9 m depth during the periods August-October 2013 (up) and August-November 2015 (down) in cauliflower grown with different timing (early and late) and doses (10 and 20 t dm ha^{-1}) of MSWC application. Vertical bars indicate ± standard error of means (3 replicates).

Table 3. Aboveground dry matter accumulation (DM), total N-uptake (N_{up}), total curd fresh weight yield (Yield), mean curd weight, and curd diameter in cauliflower grown in 2013 and 2015 with different timing (early and late) and doses (10 and 20 t dm ha^{-1}) of MSWC application. Early application was at the end of March (*i.e.*, about five months before transplanting); the late application was at the end of July (*i.e.*, about one month before transplanting).

Treatments	DM (Mg ha^{-1})		N_{up} (kg ha^{-1})		Yield (Mg ha^{-1})		Mean curd weight (gr)		Curd diameter (cm)	
	2013	2015	2013	2015	2013	2015	2013	2015	2013	2015
C10_early	7.1	5.8	172	146	31.2	20.6	1044	681	17	16
C10_late	5.1	3.9	99	67	16.5	11.5	544	373	13	13
C20_early	6.5	5.6	167	149	28.3	18.8	888	628	16	16
C20_late	4.9	2.7	120	52	20.3	6.3	651	207	13	11
N0	6.0	4.1	143	80	26.9	12.5	861	417	15	14
MIN	7.0	7.5	282	253	35.1	33.6	1049	1125	17	18
Treatment (T)	***	***	***	***	***					
Year (Y)	***	*	***	**	ns					
T × Y	**	ns	ns	-	ns					
Pooled SED	0.294	20.5	2.82	101.4	0.93					

growing season or cauliflower grown during an autumn growing season. Apart from the crop growing season, the different seasons of compost distribution tested in our experiments (*i.e*., spring or summer) had a similar effect on reducing growth in both crops. The interaction between the timing of compost distribution and the growing season seems to affect the yield response. Indeed, our experiments have demonstrated that when compost is applied a few months earlier than transplanting (*i.e*., from five to nine months before the transplanting), the suppressive effect of its application is reduced, independent of the environmental conditions.

For this reason, within all the MSWC treatments, the highest yield was recorded in the early application for tomato (in summer, nine months before transplanting) and in the early application for cauliflower (in spring, five months before transplanting) in both years. It is noteworthy that the effect of timing of compost application was particularly evident at the highest dose. Responses beyond the first crop after application may also need to be considered in relation to the type of soil and the dose of compost application. In arid and semiarid regions of Spain, Garcia *et al.* (2017) demonstrated that the benefits of a high rate of MSWC (from 40 to 120 t ha^{-1}) occurred only in the long-term period (over seven years). However, in more favourable conditions in Austria and Germany was estimated that the annually accountable N supplied from compost is on average 3% up to 10% in the first 3-4 years of compost application. In the successive 5-10 years, the amount of N annually mineralised can be 5-12% up to 20% (European Compost Network, 2010; Morra *et al*., 2021). Fagnano *et al*. (2011) found a positive effect of soil fertilisation with high doses of MSWC (30 and 60 t ha^{-1}) in lettuce grown in sandy loam soil in south Italy. Morra *et al.* (2021) pointed out that an integration with mineral N fertilisation should be performed to overcome a possible initial crop N deficiency due to N immobilisation during compost mineralisation.

In addition to the amendment effect of compost, and despite the decrease of yield in the compost amended plots, this research shows that compost use may have a positive effect in reducing N leaching risks. Indeed, the N-NO_3 concentration measured in the soil solution was lowest in all MSWC treatments in both crops compared to the MIN control. A similar conclusion was achieved in previous research (Santos *et al*., 2018; Mauceri *et al.,* 2019; Morra *et al*., 2021) that suggested how the compost may be used as a partial substitution of the mineral fertiliser without significant nitrate leaching. Willekens *et al*. (2014) found that despite abundant organic N input related to a high dose of compost application (up to 45 t ha^{-1}), the residual soil mineral N was not higher.

Conclusions

This experiment highlighted that fertilisation with only compost at relatively low doses (*i.e*., 10 and 20 t MSWC ha^{-1}) is inadequate to ensure high yield for both summer and autumn vegetables in open field conditions. However, the timing of the application of compost seems to play an essential role in minimising the crop growth reduction due to compost application. For example, in both processing tomato and cauliflower, when the MSWC was applied a few months earlier than the transplanting (*i.e*., in the previous summer in tomato and the previous spring in cauliflower), the DM and yield reduction were less pronounced than in soil where compost was applied just before transplanting.

Fertilisation with only compost limited the amount of N available to the crop and reduced the N taken up by tomato and cauliflower, generating a low N use efficiency. However, MSWC decreased the N-NO_3 concentration in the soil solution. Thus, in addition to the amendment effect, results carried out by this research show that compost may reduce N leaching risks in groundwater.

Based on our results, compost may be considered a valuable product with high environmental, social, and economic potential. However, it should be applied early before the crop season (*i.e*., from five to nine months before crop transplanting) and later to complete fertilisation with mineral N fertiliser to gain high yield, increase soil organic carbon and reduce groundwater contamination risk.

Long-term experiments with repeated organic amendments in crop rotations are recommended to fully evaluate the use of compost as a substitute for mineral N fertilisation in vegetable cropping systems.

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