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Benefits for agriculture and the environment from urban waste

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ABSTRACT

Soluble bio-based substances (SBO) that have been isolated from urban biowaste have recently been reported to enhance plant leaf chlorophyll content and growth. The same SBO have also been shown to enhance the photochemical degradation of organic pollutants in industrial effluent. These findings suggest that SBO may promote either C fixation or mineralization, according to operating conditions. The present work aims to investigate SBO performance, as a function of source material. Thus, three materials have been sampled from a municipal waste treatment plant: (i) the digestate of the anaerobic fermentation of a humid organic fraction, (ii) a whole vegetable compost made from gardening residues, and (iii) compost made from a mixture of digestate, gardening residues and sewage sludge. These materials were hydrolyzed at pH 13 and 60 °C to yield SBO that display different chemical compositions. These products were applied to soil at 30, 145 and 500 kg ha^{-1} doses for tomato cultivation. Soil and plant leaf chemical composition, plant growth, leaf chlorophyll content and CO_2 exchange rate as well as fruit quality and production rate were measured. Although it did not affect the soil's chemical composition, SBO were found to significantly increase plant photosynthetic activity, growth and productivity up to the maximum value achieved at 145 kg ha^{-1}. The effects were analyzed as a function of SBO chemical composition and applied dose. The results of this work, compared with those of previous works, indicate that urban biowaste, if properly exploited, may furnish conjugate economic and environmental benefits, within a friendly sustainable ecosystem.

Abbreviations: D, digestate; CV, whole vegetable compost; CVDF, compost from digestate, vegetable residues and sewage sludge; SBO, soluble substances.

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1. Introduction

The environmental impact of urban waste has dramatically increased as a result of increasing population, urbanization and consumption habits. This fact means society must deal with a significant economic waste management and/or disposal burden. However, it is also a potential source of benefit. Through urbanization and municipal collection practices, urban biowaste has become a low entropy sustainable source of energy and chemicals for industry and society. It provides advantages over biowaste from other sources, such as agriculture, animal husbandry or the agro industry, and is available worldwide in large quantities which are concentrated in the confined spaces of urban areas. Collection costs are paid by taxpayers. Thus, urban biowaste has been defined as a negative cost source of concentrated renewable organic matter (Sheldon-Coulson, 2007). Recent research (Montoneri et al., 2011) has shown that the recalcitrant lignin-like fraction in urban biowaste is a cost-effective source of soluble bio-based substances (SBO). SBO are described as mixtures of macromolecules with a weighted average molecular weight (Mw) ranging from 67 to 463 kg mol^{-1} and polydispersity indexes (Mw/Mn) in the 6–53 range. They are formed of long aliphatic C chains that bear aromatic rings and several functional groups, such as COOH, CON, C=O, PhOH, O-alkyl, OAr, OCO, OMe and NRR', where R and R' are alkyl or aryl substituents. These organic moieties are probably the memory of the main constituents of the sourcing bio-organic waste which are not completely mineralized during aging under aerobic fermentation conditions. The SBO bear chemical similarities with the natural organic matter (NOM) present in soil and water. For these reasons, no adverse environmental impact is expected from SBO.

A number of properties and uses have been proven for SBO that have been isolated from different urban bio-waste sources. These substances also behave like anionic surfactants because of the presence of lipophilic, aliphatic and aromatic moieties and of hydrophilic functional groups. They have accordingly been shown to be effective (Montoneri et al., 2011) as detergents, auxiliaries for textile dyeing, emulsifiers, flocculants and dispersants, binding agents for ceramic manufacture, templates for the fabrication of nanostructured materials for chemical and biochemical catalysis as well as being active agents for cleaning polluted soil via surfactant assisted washing. More recent studies point to a possible role for these substances in the ecosystem C cycle.

Studies on the *in vitro* fermentation of animal feed (Montoneri et al., 2013) and *in vivo* animal weaning (Dinuccio et al., 2013) have shown that SBO are capable of decreasing the mineralization of organic N during anaerobic digestion, when added to the cecal content of pig or rabbit feed, and therefore of reducing emissions of ammonia and greenhouse gases from animal husbandry.

Several organic molecules, typically found in the effluents of many chemical industrial processes, have been shown to degrade rapidly with relevant organic C mineralization, when exposed in solution to solar light in the presence of SBO (Bianco et al., 2010 and 2012; Avetta et al., 2013). Gomis et al. (2013) have reported that these effects derive from the capacity of SBO to interact with the target organic pollutant and form a photoactive complex, or perhaps from the presence of functional groups with strong metal chelating power.

Concurrent with the above findings is a separate study which has reported that SBO, isolated from a composted mix of food and vegetable residues and applied to soil as organic fertilizer for tomato cultivation in greenhouses, enhance leaf chlorophyll content and plant growth (Sortino et al., 2012). The idea that SBO could also promote photosynthesis was rather intriguing.

In the present work, three different SBO, hereinafter referred to by the acronyms D, CV and CVDF, were isolated from the three major products of a municipal waste treatment plant located in North Italy: D is sourced from the digestate obtained from the anaerobic digestion of the organic humid fraction; CV from the compost obtained from home gardening and public park trimmings; and CVDF from a composted mix of gardening and park trimmings, digestate and sewage sludge. The SBO were applied to soil for the cultivation of tomato at three different doses. Plant leaf CO_2 exchange rate and chlorophyll content, growth and fruit productivity were monitored. The objectives of the experimental work were (i) to find direct evidence of the effect SBO have on plant photosynthetic activity and biomass production, (ii) to study these effects as a function of dose, and (iii) to assess whether the effects are general for SBO obtained from the major product of urban waste treatment plants and/or how they are related to SBO chemical composition.

2. Materials and methods

2.1. Materials

SBO sourcing materials were obtained from the Acea Pinerolese Industriale plant located in Pinerolo (TO), Italy. The plant carried out the anaerobic and aerobic digestion of urban biowaste. Anaerobic digestion was carried out for 15 days with the organic humid fraction of urban waste from a separate source collection. This process yielded biogas and a solid digestate containing residual organic matter that was not converted into biogas. Aerobic digestion was performed on two different wastes; home gardening and park trimming residues were composted for 180 days to yield whole vegetable compost, and secondly a mix of digestate, home gardening and park trimming residues as well as sewage sludge, at a 3.5/5.5/1 respective weight ratio, which was composted for 110 days. Each of the three plant products (i.e. the digestate and the two composts), was separately further hydrolyzed with KOH alkaline water at pH 13 and 60 °C to obtain the SBO. The hydrolyzate was run through an ultra filtration polysulphone membrane with 5 kD cut off. The membrane retentate was dried at 60 °C to yield the final SBO product as black solid in a 15-20 % yield, relative to the starting material. Further experimental details for all processes and product analytical characterization have been reported by Sortino et al. (2012). The tomato (*Lycopersiconesculentum* Mill.) seeds were produced in Kenya and were supplied by Syngenta Seeds (Syngenta Seeds s.p.a., Milano, Italy). Nursery plants for transplanting in the cultivation soil were grown from these seeds.

2.2. Set up of cultivation trials

Tomato cultivation trials were carried out on the same farm as in the previously reported tomato study (Sortino et al. 2012). Farm soil was classified as loamy-sandy based on its texture: sand 79.9 $\pm$ 2.5, fine sand 5.3 $\pm$ 0.7, silt 10.6 $\pm$ 1.8, clay 4.2 $\pm$ 0.4 % w/w. The experiment was set up as a completely randomized design with 3 replications in a greenhouse constructed from 0.15 mm thick polyethylene film supported by cement and wood. Greenhouse soil was divided into 30 parcels, each containing 10 m^2 soil surface. Three control parcels had no added SBO. The other 27 parcels were divided into three groups of nine parcels each: One group was treated with D, one group with CVDF and the third group with CV. Each group of nine parcels was treated with three doses of SBO in triplicates: i.e. three plots with 30kg ha^{-1}, three plots with 145kg ha^{-1} and three plots with a 500kg ha^{-1}dose. The solid SBO were incorporated into the soil on November 21, 2011. Two days later 10 cm long nursery test plants, each with 6 true leaves, were transplanted in all parcels to yield three sets of double rows per parcel, with a distance of 120 cm between sets, 80 cm between rows in each set and 30 cm between plants in each row. Plant density was 3.3 plants m^{-2}. After transplanting, the soil was covered with white polyethylene film equipped for sub-surface drip irrigation (I think this is the correct name for the system, please check). All other cultivation details were the same for all parcels and carried out according to the protocol adopted by the hosting farm in its normal cultivation practice (Sortino et al. 2012). Thus, all plots of soil in the greenhouse had the following base mineral fertilization (Dorais, 2007; Chapagain and Wiesman, 2004): P_2O_5 60 kg ha^{-1} supplied as mineral ammonium phosphate and K_2O 100 kg ha^{-1} supplied as potassium sulfate. This was followed by the addition of the SBO, and then by nursery plant transplantation. The experimental plan was carried out over about 7 months from transplanting to harvesting (April to June 2012). Over this time, soil irrigation was performed using the drip irrigation system (Ho, 1984) to supplement natural soil water and mineral depletion and fulfil plant needs over the plant growth and production cycles. To this end, the above phosphate and sulfate products were used in conjunction with a mineral nitrogen fertilizer containing 32.4 % total N as nitrate, ammonia and urea in 1:1:2.5 weight ratio respectively. The frequency of irrigation depended on weather conditions and was the same for all soil plots. Irrigation was performed approximately every10-15 days, and covered the whole harvest production cycle in order to provide different N/K ratios according to plants' growth/production stage: i.e. 1:3 N/K from transplanting to flowering; N to encourage plant flowering; 1:2 N/K at beginning of fruit-setting of the fourth cluster; 1:1 N/K after the start of fruit ripening to promote leaf development. Throughout the entire harvest cycle the total amount of supplied nutrients were at about 800 N $kgha^{-1}$ and 1000 K $kgha^{-1}$. The plants were pruned in March in order to stop vegetative growth and enhance fruit production. Thus, monitoring of the plant biometric data ended on the same date. The soil, plants, leaves and fruit were analyzed at time intervals for chemical and physical features. Results are reported only for surveys performed at dates where significant differences were found over the previous survey.

2.3. Soil, plant and harvest analyses and measurements

Throughout the growing season, from April to late June, four plants from the central rows of each plot were selected for plant height and diameter measurements, of leaf chlorophyll content and gas exchange rate, and of fruit productivity and quality. Ripe fruit (approximately 2 kg per plot) was sampled for laboratory analyses (AOAC 1990). Ten pieces of fruit from the 2 kg sample were washed with running water to remove dirt and dried thoroughly with absorbent paper, before further analyses. The chlorophyll content of the fifth plant leaf was measured at three moments during the growing season (January 13, March 16, and May 9) by means of a portable SPAD-502 Minolta chlorophyll meter. At the same dates, leaf CO_2 gas exchange was measured at midday, using a portable infra-red gas analyzer LICOR LI-6200 (LICOR Inc., Lincoln, Nebraska, USA) with a 250 cm^2 leaf chamber. On June 10, one additional measurement of leaf chlorophyll content was performed to further monitor plant photosynthetic activity. Based on the good correlation obtained between leaf chlorophyll content and CO_2 exchange rate from the three previous measurements (see section 3), the June 10 SPAD data alone were assumed as reliable indicators of the plant photosynthetic activity at that date without the need for further CO_2 exchange rate measurements. All other analytical details relating to soil physical-chemical features, to soil and leaf mineral element content and to fruit total soluble solids, pH, titratable acidity, electrical conductivity and firmness were as previously reported (Sortino et al., 2012).

2.4. Statistical treatment of data

Data were statistically analyzed by a one-way analysis of variance (ANOVA) using COSTAT version 6.003 (CoHort Software). Differences between mean values were evaluated for significance using the Student–Newman–Keuls (SNK) test, according to Snedecor and Cochran (1989). A one-way ANOVA was adopted for statistical analysis since the experiment included a single control group for all treatments. Moreover, the effects of the rate of compost do not appear to be univocal and the main effects (product and dose) are unclear.

3. Results

3.1. Chemical nature of SBO

The SBO, derived from the digestate and composts supplied by the Acea Pinerolese municipal waste treatment plant, were obtained via the alkaline hydrolysis of the sourcing materials, followed by the filtration of the hydrolysate through a 5 kD cut-off polysulphone membrane and the drying of the retentate (see section 2.1). Thus, they are hydrolysates with molecular weight of over 5000 D. They contain water soluble polymeric molecules which, according to a previous work (Montoneri et al., 2011), may range up to several hundred kg $mole^{-1}$. Their chemical nature is identified by the concentrations of C types and functional groups, as reported in Table 1. The data show that, due to their differing origin, the SBO displayed different C type and functional group distributions. These are listed as aliphatic (Af), aromatic (Ph), methoxy (OMe), amide (CON), ammine (NR), alkoxy (RO), phenoxy (PhOY), anomeric (OCO), carboxylic acid (COOH), phenol (PhOH) and ketone (C=O) C atoms. Ranking these substances by the values of each of these C atoms is rather difficult. An easier and more meaningful way of doing this uses the following two parameters: One is the LH parameter which is given by the ratio of the sum of the lipophilic Af, Ph, OMe, CON, NR, RO, PhOY and anomeric C atoms to the sum of the hydrophilic COOH, PhOH and C=O C atoms. By this definition, LH is an index of the degree of SBO lipophilicity. The other parameter is given by the Af/Ar C ratio, where Ar is given by the sum of Ph, PhOY and PhOH C atoms. By this definition, Af/Ar indicates the type of lipophilicity. Thus, based on Table 1 data, it may be observed that the SBO obtained from the digestate (D) and from the whole vegetable compost (CV) exhibit the largest differences. The former has the lowest values for C/N elemental ratio and ash COOH acid group content, while exhibiting the highest LH and Af/Ar values. This indicates DSBO as the most lipophilic, aliphatic and least acidic product and it also displays the highest content of organic N. At the other extreme of the empirical chemical scale, CV SBO have the highest C/N ratio, the highest content of COOH acid groups and the lowest LH values. Thus, these appear to be the most hydrophilic acid substances and are characterized by the lowest content of organic N. The SBO listed in Table 1 also have different mineral compositions. The D SBO have the lowest content of mineral elements, particularly Si, Ca, Mg, Fe and heavy elements, while exhibiting the highest content of K and Na. The CV SBO are distinguished for having the highest content of Ca, Mg, Fe and Si.

3.2. Effects on soil and plant leaves

Soil was analyzed for electrical conductivity, salinity, pH, total organic C and N and for the content of several mineral elements. The analyses were performed on untreated soil and on the SBO treated soil at the applied doses of 30, 145 and 500 kg ha^{-1}. No significant SBO treatment effects were evident, from the chemical nature or the dose of the soluble substance. Typical analytical data are reported in Table 2 for the control untreated soil and for the soil treated with the highest 500 kg ha^{-1} dose of each of the three applied SBO.

Leaves were analyzed for C, N, P and several other mineral elements. The importance of these parameters and their relationships in soil and leaves are reported in more details in the specialized literature (Dorais, 2007; Pagliarulo, 2000). Generally however, the chemical analysis of leaves is an indicator of plant nutritional status and soil analyses are intended to provide guidance on the ability of soil to supply plants with the elements that are essential during the growing season. As for soil, the leaf analyses were performed for plants grown in the untreated soil and on the soil treated with the SBO at the applied doses of 30, 145 and 500 kg ha^{-1}. No significant or important differences from soil treatment were evident. Table 2 reports analytical data for the leaves of plants grown in the control soil and in the soil treated with the SBO at the highest applied dose. It can be observed that no significant differences in C, N, Cr, Pb and B leaf concentration are evident. Some statistically significant differences in the concentration values of the other elements can be picked out in the leaf chemical composition of the plants grown on the treated soil. The leaves of the plants grown on the soil treated with the D SBO seem to have the highest content of Cu and Mg. The leaves of the plants grown on the soil treated with the CVDF SBO have the highest content of Fe, and the leaves of the plants grown on the soil treated with the CV soluble substance have the highest content of Mg and K. Differences in the concentration of the main plant nutrients, N, P, K, Ca and Mg, due to the soil treatments, are not significant or were contained within 30 % of the maximum found value.

3.3. Effects on plant growth

Table 3 shows that, on January 16, no statistically significant differences in plant growth that may be caused by the SBO treatment are evident. Effects become evident at later dates. Compared to the control, the highest increase in plant growth is exhibited by the CV SBO treatments at 145 and 500 kg ha^{-1} doses, but not at the lowest 30 kg ha^{-1} dose. Treatment with CV SBO at 145 and 500 kg ha^{-1} doses caused a 6 % plant diameter increase on February 17 and a 4.8-9.7 % plant height increase on March 16. At the same date of March 16, only the CV 145 $kgha^{-1}$ treatment is shown to have caused a statistically significant plant diameter increase, of 9.4 %. The other treatments with investigated SBO gave smaller or non-statistically significant effects on plant growth.

3.4. Effects on plant photosynthetic activity

An indication of plant photosynthetic activity was obtained through measurements of leaf chlorophyll content and CO_2 exchange rate. The results are reported in Table 3. These two indicators are directly correlated according to the following equation:

$$Y = (2.80 \pm 1.11) + (0.24 \pm 0.02)X \qquad (1).$$

In this equation, Y and X are CO_2 exchange rate and the leaf chlorophyll content values, respectively. Fitting equation (1) to the experimental data yields a regression coefficient of 0.90. Table 3 also shows that both indicators increase from the first measurement performed in January through to the last one performed in May. Significant differences between treatment and control groups appear in the May measurements. The gas exchange rate of plant leaves grown on the soil treated with the CV SBO at 145 and 500 kg ha^{-1} doses is significantly the highest, 8 % higher than what was found for plant leaves grown on the control soil. The data for the other soluble substance treatments do not appear to be significantly different from those of the control plot. Only the 500 kg ha^{-1} CV soluble substance gives SPAD chlorophyll indicator values, on May 9 and June 10, which are statistically proven to be 8-10 % higher than those for the leaves of the control plants.

3.5. Effects on plant productivity

Table 4 reports fruit production data per soil hectare. These data were calculated from the measured number of pieces of fruit per plant and fruit weight. The measured values for these two indicators are not reported. They are summarized as follows. At each date reported in Table 4, the number of pieces fruit per plant ranged from 6 to 10, and showed no statistically significant differences between treatment and the control groups. Fruit weight varied from 50 to 127 g per fruit and was significantly affected by SBO treatment. The highest fruit weight (127 g) was obtained in the earliest April 20 harvest. This was given by the CVDF SBO treatment group at the 500 kg ha^{-1}dose. It was 49 % higher than the fruit weight (85 g) of the plants grown on the control plots. Generally, fruit weight tended to increase upon an increase in soluble substance dose and decreased from the first harvest on April 20 through to the last on June 20. The lowest fruit weight (50 g) was obtained from the CVDF SBO soil treatment group on June 20 at the 145 kg ha^{-1} dose. Considering the total number of pieces of fruits per plant calculated from the sum of all harvests, the highest total number of fruit pieces per plant was 55. This was obtained for the plants grown on the soil treated with the CV SBO at the 145 kg ha^{-1} dose. The corresponding value for per plants grown on the control plot was 47. The highest average fruit weight value of 92 g was found in CVDF SBO treatment group at the 500 kg ha^{-1}dose. The corresponding value for the control plot was 82 g. The differences in fruit production data shown in Table 4 therefore reflect the differences in fruit weight and number recorded for each treatment and harvest.

It can be seen from the plant productivity data in Table 4 that the earliest April 20 harvest shows a rather different pattern to the later harvests. The April 20 harvest is characterized by three main features: (i) a trend for the fruit yield to increase upon increasing treatment dose; (ii) all treatments giving significantly higher fruit yield than the control plot, except for the 30 kg ha^{-1} CV and the 145 kg ha^{-1} D treatments; (iii) the best performance was associated with the 500 kg ha^{-1}CVDF treatment. It is worth noticing that the yield obtained with this last treatment is 62 % higher than in the untreated control soil plot. By comparison, the following differences may be observed for the harvests that date later than April 20: (iv) the trend of fruit yield increasing with treatment dose is not evident or much less so; (v) the difference in fruit yield between treatment and control plots decreases; (vi) CV soluble substance soil treatment at a 145 kg ha^{-1} dose tends to give the highest fruit yield. The result of this trend is that the highest fruit yield, as a total of the seven harvests, was found in the group that was treated with CV SBO at a 145 kg ha^{-1}dose, as shown in Table 4. This yield (138.4 t ha^{-1}) is 20 % higher than in the control plot (114.1 t ha^{-1}). It is also higher than, or equal to, what was found in the plots treated with the same CV SBO at a 500 kg ha^{-1}dose, with D SBO at 145 and 500 kg ha^{-1}doses and with CVDF SBO at a 500 kg ha^{-1} dose. All other treatments are shown to give total yield values which are significantly lower than results obtained from treatment with the CV soluble substance at 145 kg ha^{-1} and were not statistically different from control plot results.

3.6. Effects on fruit quality

Table 5 reports five indicators of fruit quality. Due to the high number of data which are analyzed and discussed for each indicator, the results are presented in the following subsection dedicated to specific indicators.

3.6.1. Total soluble solids.

Table 5 shows very few statistically significant differences in fruit total solid content between the soil treatment and control soil groups. Out of 70 reported values relative to 7 harvesting dates, significantly higher total solid content values were only found in four cases: i.e. for the April 20 and May 3 CVDF at 30 kg

ha^{-1} dose harvests, for the May 3 D at 145 kg ha^{-1} dose harvest and for the June 14 CVDF at 145 kg ha^{-1} dose harvest. In all four cases, the fruit total solid content enhancement relative to the control amounts to 14-15 %.

3.6.2. pH and titratable acidity.

Table 6 shows that there are only small differences in the pH values of fruit grown on the SBO treated soil and the fruit grown on the control plot. Slightly lower pH values than control plot are observed in a few cases. These were found in the 30 kg ha^{-1} CV and CVDF treatments in the April 20 harvest, in the 145 kg ha^{-1} CV and 30 kg ha^{-1} CVDF treatments in the May 3 and June 8 harvests. Table 6 data on titratable acidity show that the titratable acidity of the fruit grown on the 500 kg ha^{-1}CV soluble substance treated soil display the highest value at all harvesting dates. These values are 23-43 % higher than those found for fruits grown on the control plot. Most of the other treatments also gave fruit with higher titratable acidity than the control plot. The average titratable acidity to total soluble solids ratio, calculated over the seven harvests, is 0.11 for fruits grown on the 500 kg ha^{-1}CV soluble substance treated soil and 0.09 for fruit grown on the control plot. Thus, fruits grown on the 500 kg ha^{-1}CV treated soil should be associated with a more acidic flavour (Mata et al., 2002; Bingqing, 2010) than those grown on the control soil.

3.6.3. Electrical conductivity

The data in Table 7 show that most of the soluble substance treatments yield fruit with higher electrical conductivity than control fruit. The 500 kg ha^{-1}CV and digestate (D) soluble substance treatments are associated with the highest electrical conductivity values found throughout most of the seven harvests. The electrical conductivity of the fruits grown on soil treated in this fashion was about 22-24 % higher than the fruits grown on the control soil.

3.6.4. Fruit firmness.

Table 7 shows that fruit firmness, on April 20 and May 3, is lower than the control in all soluble substance treatments. However, on May 12 fruit firmness for the 145 and 500 kg ha^{-1} CVSBO treatments is the highest. From May 23 through to June 14, no significant differences are observed between the control and most SBO treatments, except for the 145 kg ha^{-1} digestate (D) and 500 kg ha^{-1}CVDF SBO treatments which yielded significantly lower values than the control. On June 20, the 30 kg ha^{-1}CV and 500 kg ha^{-1}D SBO treatments are associated with the highest fruit firmness. These data, checked against Table 4 production data, show that SBO treatments give higher fruit production in the earliest harvest, but lower fruit firmness compared to the control plots. However, the firmness of the products obtained from the soil treated with SBO tends to improve and becomes higher than that of the product obtained from the untreated control soil in the later harvests. The firmness of the fruits obtained from the soil treated with the CV SBO is the highest when considering the entire period.

4. Discussion

Table 8 summarizes the observed effects of SBO treatment. The results point to CV SBO 145 kg ha^{-1} treatment being the best of the investigated treatments for use in the cultivation of tomato plants. This treatment is associated with the highest observed effects. The CV 145 kg ha^{-1} treatment yields the highest enhancements in terms of plant photosynthetic activity (8 %), plant growth (6-9 %) and total fruit productivity (20 %), as compared to the control. A search for a possible chemical composition-performance relationship in the data from Table 1 data shows that CV SBO are distinguished from D and CVDF SBO thanks to higher Ca, Mg, Fe, Si and COOH functional group content. This fact may indicate that CV SBO are capable of transporting more mineral nutrients from the soil to the plant. The N and organic C contents are also important to improving soil fertility (Dorais 2007; Fagnano et al. 2011; Furrer and Gupta 1983; Haber, 2008). Table 1 shows that D SBO give higher relative C and N content than CV and CVDF SBO. Nevertheless, D SBO performance is not as good as CV SBO under the experimental conditions chosen in this work. This fact implies that C and N contents, although important, are not the only factors that determine the performance ranking order of the investigated products. A similar observation has been reported in a previous study where CVD SBO (Sortino et al., 2012) was compared to a commercial product that contained more N due to the presence of meat, bone and animal blood meal. It is relevant at this point to mention that Sortino et al. (2012) reported that CVD SBO contain, similarly to CV, high concentrations of Si (2.49 % w/w), Fe (0.88 % w/w), Mg (0.93 % w/w), Ca (4.70 % w/w) and COOH (0.10 mol per mole of total organic C). The CVD soluble substance was also found to increase tomato plant leaf chlorophyll content by 11 %, plant diameter by 13 % and fruit ripening rate by 3-19 days, as compared to control data, whereas total plant productivity was not significantly different.

The present work, which couples leaf chlorophyll content and gas exchange measurements, provides direct evidence of photosynthetic activity enhancement by CV SBO. The relatively high mineral element content in CV SBO coupled with their COOH group content, solubility at soil pH and high hydrophilicity may be connected with their capacity to enhance plant photosynthetic activity. Although, no evidence of any increase in mineral element content was found in chemical analysis of the CV treated soil, the observed effects on plant photosynthetic activity and biomass production might be caused by relatively small amounts of the elements bound to the CV SBO organic matter, to their increased solubility at soil pH, and therefore to their capability to migrate faster from the soil to the plant together with the SBO organic moiety. Table 1 shows that, in addition to COOH groups, SBO also carry amino and phenol groups. These latter groups are able to complex and so enhance the solubility of mineral cations.

The chemical features demonstrated for CV SBO however do not help to unequivocally identify their mode of action. It is certainly intriguing to observe that the same SBO that promote plant photosynthetic activity may also promote the photo degradation of organic pollutants (see section 1). These facts indicate that, depending upon experimental conditions, CV SBO may promote opposite effects, i.e. C fixation or C mineralization. Other than allowing an intriguing empirical observation to occur, the available data are not comprehensive enough to assess any mechanistic relationship between effects on plant photosynthetic activity and on waste water remediation processes. In the latter case, SBO were tested in a homogeneous solution containing the probe substrate, in order to function as photo sensitizers. Under the experimental conditions of the present work, SBO must undergo a number of mass transfer processes from the soil to the plant in order to perform their action. In these processes, SBO may undergo several chemical and biochemical reactions in the soil and in the plant. Thus, proving the role of SBO as sensitizers or catalysts that also promote photosynthesis is rather hard. A number of other reasons should account for the observed performance of CV SBO as plant growth promoters. They could act as bio-effectors. They might stimulate the uptake of soil nutrients from roots with a hormone-like effect and/or plant growth by promoting rhizobacteria.

Within its experimental constraints, the present work has some other practical relevance. It provides new important information to guide the use of products derived from municipal wastes for optimum performance in agriculture. For example, information that will be of primary interest to farmers is early season plant production. High early plant productivity allows the farmer to obtain more benefit from a higher fruit market price. The results of this work show that, for the early April 20 harvest, the CVDF 500 kg ha^{-1} treatment exhibits rather exceptional performance, yielding 62 % higher plant productivity than the control plot plant. However, the fruit firmness of this higher production is significantly lower than that of the fruits grown in the control plot. Firmness, as measured by the resistance of the fruit to crushing pressure, allows fruits to withstand mechanical impact and have longer shelf life. This parameter is particularly important for fruit products. The trade off between higher productivity and lower fruit firmness needs to be properly managed under real commercial conditions.

Other important economic and environmental implications of this work can be found in the CV dose effect. The data in Table 4 show that, whereas the CV SBO 145 kg ha^{-1} dose is significantly more effective than the 30 kg ha^{-1} dose, no significantly higher effect is demonstrated by increasing the SBO dose to 500 kg

ha^{-1}. Furthermore, the higher 500 kg ha^{-1} CV dose was not proven to give significantly higher fruit yield than the control plants. It is also relevant at this point to observe that, while 20 % higher plant productivity relative to the untreated soil plot was observed with the 145 kg ha^{-1} applied CV dose in this work, the previous tomato cultivation study (Sortino et al., 2012) gave no significant plant productivity difference between plants grown on the soil treated with the CVD SBO at 1550 kg ha^{-1}dose and the control plants. Furthermore, in other cultivation studies performed with one-two order of magnitude higher doses of different municipal solid waste composts (Tzortzakis et al., 2012; Maynard et al., 1995; Ozores-Hampton et al. ,1995; Bryan and Lance, 1991) or conventional fertilizers (Baldantoni et al.2010), no real benefits have been shown by increasing doses, whereas concern for environmental pollution has been raised. The highest plant productivity, attained in the present work with a 145 kg ha^{-1} CV SBO dose, paves the way for agriculture practices with increased productivity and fertilizer cost reduction. The environmental relevance of this work lies in the fact that, in addition to allowing maximum plant productivity to be reached, the low SBO dose minimizes the risk of the potential environmental impact caused by repeated fertilizer application (Giola et al. 2012).

5. Conclusion

The SBO, obtained by the alkaline hydrolysis of whole vegetable municipal waste compost, have been proven to enhance tomato plant photosynthetic activity and productivity, relative to control plants. The results of this work, and of previous works performed on the properties and many other uses of these substances for the manufacture of industrial and consumers' products, for the remediation of contaminated soil and waters and for decreasing the environmental impact of animal husbandry practices, indicate that urban biowaste, if properly exploited, may have an important role in the ecosystem. They are source of soluble substances which can replace synthetic chemicals in many applications thanks to their surfactant properties. At the same time, these soluble substances may enter the C cycle through agriculture to promote the production of biomass for human consumption, which will in turn generate other renewable organic C waste.

With specific focus on agriculture, this work points to relevant economic and environmental benefits that may derive from the use of SBO. It also highlights the significant differences in chemical composition and performance found in SBO isolated from different materials which are either pre-treated by anaerobic or aerobic fermentation. Potential users should be aware of such differences. The results of this work certainly offer worthwhile scope for further trials which would test SBO, isolated from other biowaste sources and/or in different experimental conditions, in order to understand the reasons for their performance and exploit their full potential. The development of a self-sustainable ecosystem based on cycling renewable organic C between wastes and added value products appears to be a feasible future goal.

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