# Title: Short term phosphorus release from composts in a soil-plant system: the effect of elemental sulphur ($S^0$) addition

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## Abstract

One compost from green waste (GW) and one from bio-waste and sewage sludge (BWSC) were compared for their capacity to release inorganic P ($P_i$), and labile-organic P ($P_o$) over 56 days of incubation in a calcareous soil (30 mg P kg$^{-1}$), in comparison with unamended control (Ctrl) and a chemical P source (P-chem), in combination or not with elemental sulphur ($S^0$) at 50 and 100 mg S g$^{-1}$ compost. Furthermore the plant P uptake was assessed after a 56 days pot test on maize (same soil and P rate). In the soil test Ctrl $S_{100}$ and GW $S_{100}$ had the greatest pH reduction (-0.8 vs. -0.6), BWSC $S_{100}$ attained to -0.5. At the same time $P_i$ increased in Ctrl $S_{100}$ and GW $S_{100}$ (+14 and +20%), being limited in BWSC $S_{100}$ (+6%). Pot test showed GW S- and BWSC S- ensure similar available P: 12.0 vs. 12.5 mg pot$^{-1}$ (+45 and +51% vs. Ctrl S-), attaining to 95% (GW) and 99% (BWSC) relative efficiency in comparison to P-chem (12.6 mg pot$^{-1}$). GW $S_{50}$ and GW $S_{100}$ increased the plant P uptake in (+7 and +11% vs. GW S-), while BWSC performed negatively at both $S^0$ levels (-4% on average). $S^0$ strongly mobilized native soil P (+35%, on average), and P from GW (+9%). The negative performance of BWSC and P-chem following the $S^0$ treatment was related to intense Fe accumulation in root (4.74 and 3.98 mg g$^{-1}$) corresponding to +70 and + 30% in comparison to GW.

**Keywords**: labile-organic P; maize; calcareous soil; iron

## 1. Introduction

Phosphorous (P) is essential for plant growth, this is widely utilized to sustain high crop productivity, in this frame more than 80% of the yearly world's P flow is utilized for these purpose [1]. The P utilized for the fertilizers production is mainly derived from rock phosphate which is a non-renewable source. In this scenario ever increasing interest is recently paid to the rational exploitation of P from recycled organic matter (OM) like composts [2]. Composts can represent a valuable source of nutrients for plants, mainly nitrogen (N) and P, while the former has been widely investigated, more deep information are still missing for the latter [3]. Composts can derive from many different kind of organic wastes (bio-waste, green waste, waste water and agro-industrial sewage sludge), thus showing deeply varying characteristics. For these reasons composts can display very different P content, besides to various content of calcium (Ca), magnesium (Mg), iron (Fe) and aluminium (Al), which can deeply affect the P extractability thus modifying the potential P plant availability in the end [4; 2]. Moreover once in soil, P from composts can further react with Ca- and Mg- compounds at sub-alkaline/alkaline pH typical of calcareous soils, being this rapidly fixed therefore reducing the P utilization by plants [5;6]. In this frame to increase the P mobility and its availability in calcareous soils is often reported in literature the utilization of acidifying agents such as elemental sulphur [7; 8; 5]. The oxidation of $S^0$ to $SO_4^{--}$ operated by sulphur oxidizing bacteria (SOB) produce $H^+$, inducing the pH decreasing in soil, thus promoting higher P mobility, beside to the plant-available P increases [9; 10; 11]. It is widely recognized that the SOB activity is related to the organic carbon availability in soil [12; 10], in this light the addition of recycled OM can stimulate their action, being the coupled utilization of compost and $S^0$ a possible winning strategy to maximize the P mobilization and further utilization by plants in calcareous soils [9]. On the other hand the pH variation following the oxidation of $S^0$ can differently affect the P release from the various composts on the basis of their abovementioned inherent characteristics (i.e. Ca, Fe). From what exposed above it appears therefore the course of potentially available P from composts added to the soil is the result of the interaction between composts and soil characteristics. To study these aspects laboratory soil incubations can be very informative. In this frame the available P (in calcareous soils) is generally estimated by assessing inorganic P extractable in $NaHCO_3$ [13]. At the same time some researches focused on the role of "organic" P extracted by Na-bicarbonate [14]; these forms can be directly utilized by plants or utilized after further mineralization [15-16]. Beside to P also other elements can be investigated in this extracts such as Ca, Fe, Al, which are recognized to regulate the P availability in such type of soil in the medium- and the long-term [17]. In this light following the kinetics of both inorganic and "organic" P release after the soil addition of composts beside to the investigation of the accompanying cations (Ca; Fe; Al), can be helpful in the whole comprehension of dynamics following soil amending. In addition to soil incubations, the utilization of plant tests in pot can be really informative to assess the P apparent utilization of the added P with organic sources [5; 18]. Plants cultivated in pot under well controlled conditions can be useful to validate the information obtained by chemical investigation and soil incubations to give a more complete insight to the topic. Corn (*Zea mays* L.) is recognized to be one of the most world-wide diffused crop, moreover this requires great amount of P to sustain its high productivity appearing very suited for this kind of test [5]. Composts have been widely utilized as amendments, using these as basal dressing with the aim to increase the long term soil fertility, few are the investigation done on this kind of products about their fertilizing capacity in the short term. The utilization of recycled OM can be a valuable source of P for plants, this coupled to the utilization of natural acidifying agents (such as $S^0$), can be an economic and friendly strategy to increase the plant available P from this kind of products. In this light we have selected two stable composts with contrasting characteristics, one from green waste (GW), and one from a mixture of bio-waste, urban sewage sludge and green waste (BWSC). On these composts we have made the P fractionation via sequential chemical extraction (SCE). We have then assessed the course of inorganic- and organic- P besides to the determination of the accompanying cations (Ca; Fe; Al), following the addition of composts during a 56 days incubation in a calcareous soil (30 mg of P $kg^{-1}$), in combination or not with $S^0$ at two levels (50; 100 mg $S^0$ $g^{-1}$ compost). A non amended control and a chemical P source [$Ca(H_2PO_4)_2$ $H_2O$] were added as reference. In addition we have made a 56 days pot test on corn, with the same soil and the same treatments and rate to assess the plant P uptake in the same timeframe. The aims of this work were: (i) assess the short term course of inorganic- and organic- P from the different composts in combination or not with $S^0$; (ii) assess the interactive effect of composts and $S^0$ on the P uptake of corn.

## 2. Materials and methods

### 2.1. Organic products

In this work were compared two composts from different raw materials, one from green waste (GW), and one from a mixture of bio-waste, urban sewage sludge and green waste (BWSC). The first was obtained after a 90 days open windrow composting with weekly turning, the second one was subjected to accelerated oxidation with forced air ventilation followed by a curing phase, totally 90 days. All the fresh products were analyzed for pH, electric conductivity (EC; $H_2O$ 1:10), total solids (TS), and volatile solids (VS) content. The organic products were then air dried, ball milled and analyzed for the main physical-chemical parameters. On the air dried products the total carbon (TC) and total nitrogen (TN) were determined by using an elemental analyzer (Thermo Fisher Scientific). Total nutrients and trace elements content was determined by ICP (Inductively Coupled Plasma-OES, Spectro Arcos, Ametek) on ≈300 mg of samples after microwave assisted digestion with 65% $HNO_3$ + 37% HCl + 30% $H_2O_2$, all the analysis were done in two replicates. The OUR was determined according to Grigatti et al. [19], in three replicates. The main physico-chemical characteristics of organic products are reported in Table 1. The addition of elemental sulfur was done to each compost at two levels (50 and 100 mg $S^0$ $g^{-1}$ compost; $S_{50}$ and $S_{100}$), by accurately mixing in a mortar the air-dried and ball milled compost with micronized $S^0$ at the calculated rate to obtain an homogenous mixture.

## 2.2. Sequentially extractable phosphorus

The phosphorous fractionation was done according to Dou et al. [20]. Briefly, the air-dried and ground samples of compost were sequentially extracted with deionized water ($H_2O$); 0.5M $NaHCO_3$ (pH 8.5); 0.1N NaOH; 1N HCl, then the residual P was determined after 96% $H_2SO_4$ + 30% $H_2O_2$ hot digestion. Each extraction was done in two replicates, this was 24 h long. After this time samples were centrifuged and the supernatant was separated via filtration (Whatman #42). The recovered pellets were submitted to the following extraction. The inorganic P ($P_i$) was colorimetrically determined on the extracts according to Murphy and Riley [21]. Total P in the extracts ($P_{icp}$) was determined by ICP-OES [20]. The sequentially extracted P forms were called $H_2O$-P; $NaHCO_3$-P; NaOH-P, HCl-P, $H_2SO_4$-P. Organic P ($P_o$) was calculated as the difference between $P_{icp}$ and $P_i$ in the first four fractions ($H_2O$; $NaHCO_3$; NaOH; HCl). The P recovery was calculated as $P_i$ or $P_o$/total P determined by separated acid digestion (65% $HNO_3$ + 37% HCl + $H_2O_2$) and expressed as %.

## 2.2. Soil incubation

The soil used for soil incubation and pot trial was collected from the top layer in a field in the Po Valley (Bologna, Italy), the main soil characteristic are described in a previous work by Grigatti et al. [18]. The measured Olsen-P was at 9 mg $kg^{-1}$ (as P). This was sieved at 2 mm, a quantitative corresponding to 200 g of dry soil were placed in plastic vessels provided with a perforated cap, and pre-incubated in the dark at 25 °C at 60% WHC for three weeks. The moisture was reintegrated by weighing twice a week. After this period the organic amendments were added at the rate of 30 mg P $kg^{-1}$ soil, in combination or not with $S^0$ at two levels ($S_{50}$ and $S_{100}$). Besides to this a unamended control and a chemical P source [$Ca(H_2PO_4)_2$ $H_2O$] was added as reference, in combination or not with $S^0$. The amount of $S^0$ added to the unamended soil and to the P-chem was the same of the amount added with composts, this corresponded to 350 and 700 mg $kg^{-1}$ soil. During the 56 day of incubation the soil pH was determined in water 5 times (day: 0, 14, 28, 42, 56), in addition in the same sampling date we have extracted the soil with 0.5M $NaHCO_3$ pH 8.5, on this extracts we have determined the total P ($P_{icp}$) via ICP (Inductively Coupled Plasma-OES, Spectro Arcos, Ametek) and the inorganic forms $PO_4^{--}$-P ($P_i$) via the molybdenum blue method (Murphy and Riley, 1962). Organic-P ($P_o$) was determined as differences between $P_{icp}$ and $P_i$. On the same extracts were determined also the other main elements (Fe, Al, Ca, Mg) via ICP.

## 2.3 Plant test

Similarly to what done for the soil incubation the organic amendments were added to the soil at the rate of 30 mg P $kg^{-1}$ soil, in combination or not with $S^0$ at two levels ($S_{50}$ and $S_{100}$). Besides to this a unamended control and a chemical P source [$Ca(H_2PO_4)_2$ $H_2O$] was added as reference, in combination or not with $S^0$. Two liter plastic pots (∅ 140 mm × h 150 mm) were filled with 1 liter of inert material (agricultural light expanded clay) and 1 kg of each different treated soil in 3 replicates arranged in a completely randomized design. Pots were seeded with two seeds of corn (Zea Maize), cv. Korimbus (KWS, Germany), covered with a thin layer of sand to prevent drying, watered and placed in a green house at 14-10 h day-night photoperiod at 15-28°C (±3 °C) day-night temperature, the light was ensured by 6 Philips Master Tld 58W-840 tubes. Plants were grown in a nitrogen non-limiting environment; for this purpose, an $NH_4NO_3$ + $KNO_3$ solution was applied 6 times during the plant growth cycle accounting for 300 mg N $kg^{-1}$ and 58 mg K $kg^{-1}$ of soil at the end. After emergence, plants were thinned to one pot-1, regularly watered with tap water to keep soil at 60% WHC. At each harvest (day 56), corn plants were cut 2 cm above ground and collected. The plant dry biomass was determined after drying plant tissue at 60°C for 3 days. The roots were divided from the soil with by water-sieving separation, and the root biomass was then treated as abovementioned for plant tissue. The soil separated by roots was collected, on this was determined the pH and the EC. On plant tissue (shoots and roots), the total P content (besides to other elements: Fe, Al, Ca, Mg) was determined by means of ICP after 65% $HNO_3$ + 30% $H_2O_2$ microwave digestion.

### 2.4 Statistics

The data from the pot test were analysed by two way ANOVA using Statistica 7.0 (StatSoft, USA), the mean separation was done accordingly the Student-Newman-Keuls at $P < 0.05$.

## 3. Results

### 3.1. Compost characteristics

Table 1 shows that GW compost had lower pH compared to BWSC (7.74 vs. 8.35), besides to the different TS content (55 vs. 89%), the two compared products showed also varying VS content (57.1 vs. 43.6 %). Contextually the C content was higher in GW in comparison to BWSC (36.4 vs. 22.2%). These besides to the different N content (1.90 vs. 2.26%) reflected on varying C/N ratio (19 vs. 9.8). Both composts resulted well stabilized showing OUR values below 15 mmol$O_2$ $kg^{-1}$ VS $h^{-1}$. GW in comparison to BWSC had the lowest P content (2.94 vs. 4.32 mg $g^{-1}$), besides to Ca (29.7 vs. 46.2 mg $g^{-1}$), Fe (9.3 vs. 14.6 mg $g^{-1}$) and Al (12.6 vs. 15.5 mg $g^{-1}$), while Mg and Mn were found at similar level in both compost (6.6 and 0.43 mg $g^{-1}$, on average). The ratio between elements was very similar in both composts: Ca:P (10.1 vs. 10.7), Fe:P (3.2 vs. 3.4), Al:P (4.3 vs. 3.6), Mg:P (2.1 vs. 1.5).

**Table 1 –** Main characteristics of the compared compost

| Parameter | Compost | |
|---|---|---|
| | GW | BWSC |
| **pH ($H_2O$)** | 7.74 | 8.35 |
| **TS (%)** | 54.6 | 88.6 |
| **VS (%)** | 57.1 | 43.6 |
| **TC (%)** | 36.4 | 22.2 |
| **TN (%)** | 1.90 | 2.26 |
| **C:N** | 19 | 9.8 |
| **OUR (mmol $O_2$ $kg^{-1}$ VS $h^{-1}$)** | 6.0 | 2.0 |
| **P (mg $g^{-1}$)** | 2.94 | 4.32 |
| **Ca (mg $g^{-1}$)** | 29.7 | 46.2 |
| **Fe (mg $g^{-1}$)** | 9.3 | 14.6 |
| **Al (mg $g^{-1}$)** | 12.6 | 15.5 |
| **Mg (mg $g^{-1}$)** | 6.25 | 6.27 |
| **Mn (mg $g^{-1}$)** | 0.39 | 0.46 |
| | | |
| **Ca:P** | 10.1 | 10.7 |
| **Fe:P** | 3.2 | 3.4 |
| **Al:P** | 4.3 | 3.6 |
| **Mg:P** | 2.1 | 1.5 |

## 3.2. Phosphorus fractionation

Table 2 shows the results from SCE. GW showed higher labile P ($H_2O$ + $NaHCO_3$) in comparison to BWSC (0.89 vs. 0.75 mg $g^{-1}$), being this mainly inorganic in both the compared products (87 vs. 93 %). Also similar in both composts was the alkali extractable P being at about 0.55 mg $g^{-1}$ on average. GW showed 25% of inorganic P in this fraction, while BWSC showed 100% inorganic P in the alkali extract. At last we found notably high difference in the HCl-P fraction being 0.88 mg $g^{-1}$ in GW and more than three times higher in BWSC (2.82 mg $g^{-1}$), these representing 38 and 68% of total extractable P. Residual P was negligible in GW being at higher level in BWSC (0.05 vs. 0.57 mg $g^{-1}$). The total P recovery varied between 79 and 109% (GW and BWSC). Overall the P fractionation showed in GW: HCl (50%)> $H_2O$ (13%)> $NaHCO_3$ (19%) = NaOH (19%); while BWSC: HCl (68%)> NaOH (14%)> $NaHCO_3$ (13%)> $H_2O$ (5%).

**Table 2 -** Phosphorus recovered during the sequential extraction of the selected composts

| **P forms/Extractant** | **Compost** | |
|---|---|---|
| | **GW** | **BWSC** |
| | mg P mg$^{-1}$ | |
| **Inorganic P** | | |
| **$H_2O$-P** | 0.24 | 0.16 |
| **$NaHCO_3$-P** | 0.53 | 0.54 |
| **NaOH-P** | 0.13 | 0.58 |
| **HCl-P** | 0.71 | 2.82 |
| **Σ $P_i$ Fractions** | *1.60* | *4.09* |
| **Organic P** | | |
| **$H_2O$-P** | 0.12 | 0.05 |
| **$NaHCO_3$-P** | nd | nd |
| **NaOH-P** | 0.40 | nd |
| **HCl-P** | 0.17 | nd |
| **Σ $P_o$ Fractions** | *0.69* | *0.05* |
| **Residual P ($H_2SO_4$-P+$H_2O_2$-P)** | *0.07* | *0.57* |
| **Total P** | | |
| **Σ ($P_i$ + $P_o$)** | *2.26* | *4.14* |
| **Σ ($P_i$ + $P_o$ + residual P fractions)** | *2.33* | *4.71* |
| **By separate $HNO_3$+HCl digestion** | *2.94* | *4.32* |
| **% recovery [Σ ($P_i$ + $P_o$)/total $HNO_3$+HCl-P]** | 77 | 96 |
| **% recovery [Σ ($P_i$ + $P_o$ + residual P fractions)/total $HNO_3$+HCl-P]** | 79 | 109 |

### 3.3 Soil pH during the soil incubation

Table 3 shows the soil pH ($H_2O$) during the 56 days of the incubation. At the beginning of the incubation the unamended soil without the sulphur addition (Ctrl S-) showed lower pH in comparison to both Ctrl $S_{50}$ and Ctrl $S_{100}$ (7.47 vs. 7.80, on average). This treatment (Ctrl S-) showed almost linear pH increase throughout the incubation, attaining to pH 7.82 in the end. Unamended control soil showed the $S^0$ addition produced the highest pH reduction at day 42, this was detected at 7.25 and 6.87 ($S_{50}$ vs. $S_{100}$), while later both $S^0$ levels attained to similar pH showing pH 7.58 and 7.41 in the end. Amongst the soil treated with compost GW S- showed almost linear pH increase in time reaching pH 7.89 after 56 day of incubation. GW at both $S^0$ levels ($S_{50}$ and $S_{100}$) showed similar trend, decreasing down to pH ≈7.17 ad day 42, performing an increase in the end (pH, 7.59 vs. 7.28).

**Table 3 –** Course of pH (in $H_2O$) during the soil incubation.

| **Treatment** | **$S^0$** | **Days of incubation** | | | | | |
|---|---|---|---|---|---|---|---|
| | | **0** | **14** | **28** | **42** | **56** | |
| | | | | | | | Average |
| **Control** | **0** | 7.47 | 7.57 | 7.54 | 7.69 | 7.82 | ***7.62*** |
| | **50** | 7.81 | 7.41 | 7.41 | 7.25 | 7.58 | ***7.49*** |
| | **100** | 7.78 | 7.43 | 7.08 | 6.87 | 7.41 | ***7.31*** |
| | Average | ***7.69*** | ***7.47*** | ***7.34*** | ***7.27*** | ***7.60*** | |
| | | | | | | | Average |
| **GW** | **0** | 7.50 | 7.75 | 7.55 | 7.66 | 7.89 | ***7.67*** |
| | **50** | 7.48 | 7.62 | 7.17 | 7.38 | 7.59 | ***7.45*** |
| | **100** | 7.53 | 7.47 | 7.16 | 7.13 | 7.28 | ***7.31*** |
| | Average | ***7.51*** | ***7.61*** | ***7.29*** | ***7.39*** | ***7.59*** | |
| | | | | | | | Average |
| **BWSC** | **0** | 7.52 | 7.65 | 7.58 | 7.30 | 7.71 | ***7.55*** |
| | **50** | 7.50 | 7.42 | 7.47 | 7.21 | 7.43 | ***7.41*** |
| | **100** | 7.49 | 7.12 | 7.15 | 7.07 | 7.35 | ***7.24*** |
| | Average | ***7.51*** | ***7.40*** | ***7.40*** | ***7.20*** | ***7.50*** | |
| | | | | | | | Average |
| **P-Chem** | **0** | 7.72 | 7.78 | 7.66 | 7.51 | 7.83 | ***7.70*** |
| | **50** | 7.70 | 7.50 | 7.20 | 7.23 | 7.59 | ***7.45*** |
| | **100** | 7.69 | 7.62 | 7.27 | 6.96 | 7.60 | ***7.43*** |
| | Average | ***7.70*** | ***7.63*** | ***7.37*** | ***7.24*** | ***7.67*** | |

The other compost (BWSC S-) showed slightly higher pH with respect to control soil at the beginning of the incubation (pH, 7.52 vs. 7.47). This compost (BWSC S-) showed also slight pH reduction at day 42 (pH, 7.30) attaining to pH 7.71 in the end. The utilization of $S^0$ induced a slow pH decrease in BWSC $S_{50}$. This treatment (BWSC $S_{50}$) reached pH 7.21 ad day 42, performing a further increase in the end (pH, 7.43). Conversely BWSC $S_{100}$ showed a rapid pH decrease reaching pH 7.12 after two weeks, this showed further decrease down to 7.07 (day 42), performing further increase in the end (pH 7.43). At last P-chem S- attained at the higher pH values in the begging (pH, 7.72), keeping fairly constant values throughout the incubation, a part a small decrease at day 42 (pH, 7.51). This treatment (P-chem S-) had also notably high pH in the end (pH, 7.83). In this treatment (P-chem) a pH reduction was detectable as function of the $S^0$ application down to 7.20 (day 28) and 6.96 (day 42) in $S_{50}$ and $S_{100}$. Both $S^0$ levels showed a common increase in the end at pH ≈7.60.

### 3.4. Inorganic and organic P course during the soil incubation

$P_i$ and $P_o$ determined during the soil incubation of the compared products are reported in Table 4. Unamended control soil (Ctrl S-) performed the lowest $P_i$ throughout the incubation, attaining to 8.1 mg $kg^{-1}$ (on average). In comparison to Ctrl S-, both Ctrl $S_{50}$ and Ctrl $S_{100}$ had higher $P_i$, attaining to 8.8 and 8.5 mg $kg^{-1}$ as mean value throughout the incubation. Amongst the organic products GW S- showed the highest $P_i$ at the beginning of the incubation (13.9 mg $kg^{-1}$). This product showed decreasing $P_i$ in the first two weeks of incubation (10.7 mg $kg^{-1}$, on average), keeping fairly constant level until the end (10.8 mg $kg^{-1}$). $P_i$ from GW did not showed clear benefit following sulphur applications.

**Table 4 –** Inorganic and organic phosphorus determined in the $NaHCO_3$ extracts during the incubation.

| | | **Inorganic-P** | | | | | | **Organic-P** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatment** | **$S^0$** | **Days of incubation** | | | | | | **Days of incubation** | | | | | |
| | | **0** | **14** | **28** | **42** | **56** | ***Average*** | **0** | **14** | **28** | **42** | **56** | ***Average*** |
| **Control** | **0** | 9.2 | 7.5 | 7.7 | 7.7 | 8.4 | ***8.1*** | 0.0 | 2.0 | 1.9 | 1.0 | 1.1 | ***1.1*** |
| | **50** | 9.9 | 7.9 | 8.9 | 8.2 | 9.2 | ***8.8*** | 0.0 | 1.9 | 1.5 | 0.9 | 1.0 | ***0.9*** |
| | **100** | 9.1 | 7.6 | 8.6 | 8.0 | 9.1 | ***8.5*** | 0.0 | 2.0 | 1.3 | 1.3 | 1.7 | ***1.2*** |
| | ***Average*** | ***9.4*** | ***7.7*** | ***8.4*** | ***7.9*** | ***8.9*** | | 0.0 | ***2.0*** | ***1.6*** | ***1.1*** | ***1.3*** | |
| **GW** | **0** | 14.4 | 10.6 | 11.2 | 11.3 | 10.2 | ***11.6*** | 0.3 | 2.7 | 1.7 | 1.1 | 1.4 | ***1.4*** |
| | **50** | 13.7 | 10.8 | 11.9 | 11.8 | 10.6 | ***11.8*** | 0.7 | 1.7 | 1.5 | 1.5 | 1.7 | ***1.4*** |
| | **100** | 13.5 | 10.8 | 11.1 | 11.7 | 11.5 | ***11.7*** | 0.0 | 2.8 | 1.4 | 1.5 | 2.3 | ***1.6*** |
| | ***Average*** | ***13.9*** | ***10.7*** | ***11.4*** | ***11.6*** | ***10.8*** | | 0.3 | ***2.4*** | ***1.5*** | ***1.4*** | ***1.8*** | |
| **BWSC** | **0** | 12.4 | 10.4 | 12.2 | 10.7 | 12.3 | ***11.6*** | 0.5 | 2.4 | 0.9 | 1.6 | 1.1 | ***1.3*** |
| | **50** | 12.6 | 10.6 | 13.2 | 10.7 | 11.7 | ***11.7*** | 0.0 | 2.4 | 0.3 | 1.9 | 2.4 | ***1.3*** |
| | **100** | 11.7 | 9.8 | 12.5 | 10.7 | 11.4 | ***11.2*** | 0.2 | 3.3 | 1.0 | 2.4 | 1.7 | ***1.7*** |
| | ***Average*** | ***12.3*** | ***10.3*** | ***12.6*** | ***10.7*** | ***11.8*** | | ***0.1*** | ***2.7*** | ***0.7*** | ***1.9*** | ***1.7*** | |
| **P-Chem** | **0** | 29.8 | 16.1 | 17.1 | 12.6 | 13.3 | ***17.8*** | 8.5 | 5.1 | 1.3 | 0.8 | 2.8 | ***3.7*** |
| | **50** | 37.0 | 18.5 | 18.6 | 14.2 | 16.1 | ***20.9*** | 0.0 | 5.2 | 2.6 | 1.4 | 2.2 | ***2.3*** |
| | **100** | 36.9 | 18.1 | 18.4 | 15.2 | 14.4 | ***20.6*** | 1.5 | 4.9 | 2.3 | 1.5 | 1.2 | ***2.3*** |
| | ***Average*** | ***34.5*** | ***17.6*** | ***18.0*** | ***14.0*** | ***14.6*** | | ***3.4*** | ***5.1*** | ***2.1*** | ***1.2*** | ***2.0*** | |

The other compost (MSCW S-) showed higher $P_i$ in comparison to the control soil (12.4 vs. 9.2 mg $kg^{-1}$) at the beginning of the incubation, keeping this differences in time (11.6 vs. 8.3 mg $kg^{-1}$, on average). Moreover BWSC showed higher $P_i$ throughout the incubation in comparison to the control soil, at both the sulphur levels (11.5 vs. 8.7 mg $kg^{-1}$, on average). The chemical reference (P-chem) showed the highest $P_i$ at the begging of the soil test 34.5 mg $kg^{-1}$ (on average), performing also the greatest mean value in time (≈20 mg kg$^{-1}$). P-chem showed the greatest $P_i$ reduction at the first sampling (day 14; -50%), keeping fairly constant value until the end. Very different outcomes were registered about the $P_o$ course: at the beginning of the incubation this was detected at very low level in Ctrl S- (0.1 mg kg$^{-1}$), performing the best after two weeks (2.0 mg kg$^{-1}$). Later, Ctrl S- showed decreasing $P_o$, attaining to 1.3 mg kg$^{-1}$ in the end (on average). $P_o$ from Ctrl S- attained to 1.1 mg kg$^{-1}$ (on average), irrespective of the sulphur addition. $P_o$ from both Ctrl $S_{50}$ and Ctrl $S_{100}$ showed similar outcomes throughout the incubation (0.9 vs. 1.2 mg kg$^{-1}$, on average). Amongst the organic products GW S- mimicked Ctrl S-. $P_o$ from GW S- peaked after two weeks (2.4 mg kg$^{-1}$, on average), showing a decreasing pattern during the incubation, attaining to 1.8 mg kg$^{-1}$ in the end (-25%). GW $S_{50}$ and GW $S_{100}$ did not showed notably high $P_o$ variation in comparison to GW S-. Also the other tested product (BWSC S-) showed small $P_o$ value in the beginning (0.1 mg kg$^{-1}$, on average). Later (day 14) BWSC S- showed higher $P_o$ in comparison to control (2.7 vs. 2.0 mg kg$^{-1}$, on average), thus performing a decrease down to 1.7 mg kg$^{-1}$ at the end of the incubation (-40%). BWSC S- and BWSC $S_{50}$ showed the same $P_o$ throughout the incubation (1.3 mg kg$^{-1}$, on average), attaining to higher $P_o$ only in $S_{100}$ (1.7 mg kg$^{-1}$).

### 3.5 Metals release during the soil incubation

In Table 5S are reported the data of selected metals (Fe, Cu, Ca, Mg), measured in the bicarbonate extracts obtained during the incubation of the compared products. From the data appears that control soil (Ctrl S-) had the lowest extractable Fe in the begging of the incubation (2 mg kg$^{-1}$), the sulphur addition attained to 2.2 and 2.7 mg Fe kg$^{-1}$ ($S_{50}$ vs. $S_{100}$). From the same table it appears therefore the extractable Fe kept fairly constant level in Ctrl S- throughout the incubation (2 mg kg$^{-1}$, on average), while it firstly decreased in Ctrl $S_{50}$ and Ctrl $S_{100}$ (down to 1.8 and 2.3 mg kg$^{-1}$), performing further Fe increase in the end, at both sulphur levels (3.3 vs. 3.7 mg kg$^{-1}$). At the beginning of incubation the bicarbonate extractable Fe from GW S- was in the same range of unamended soil (2.8 vs. 2.3 mg kg$^{-1}$, on average). This showed also fairly constant level throughout the incubation, only GW $S_{100}$ had a slight increase in the end (3.5 mg kg$^{-1}$). At the same sampling time (day 0) the other compost (BWSC S-) showed notably higher extractable Fe in comparison to control soil (3.6 vs. 2.3 mg kg$^{-1}$, on average). This compost (BWSC S-) after slight initial decrease, performed constant increase up to 4.5 mg kg$^{-1}$ in the end (on average). At increasing application of sulphur (S-; $S_{50}$; $S_{100}$) we found decreasing extractable Fe (3.9; 3.8; 3.7 mg kg$^{-1}$, on average). At last P-chem showed very low variation about $NaHCO_3$ extractable Fe, regardless of time and sulphur level.

### 3.6 Relationships between factors affecting P release in soil during the incubation

Figure 1 shows the dendrogram of the selected variables, from this figure we can observe as Ca and Mg are very well related forming a cluster. From the same figure we can observe also that Fe, Cu and $P_o$ which are well clustered.

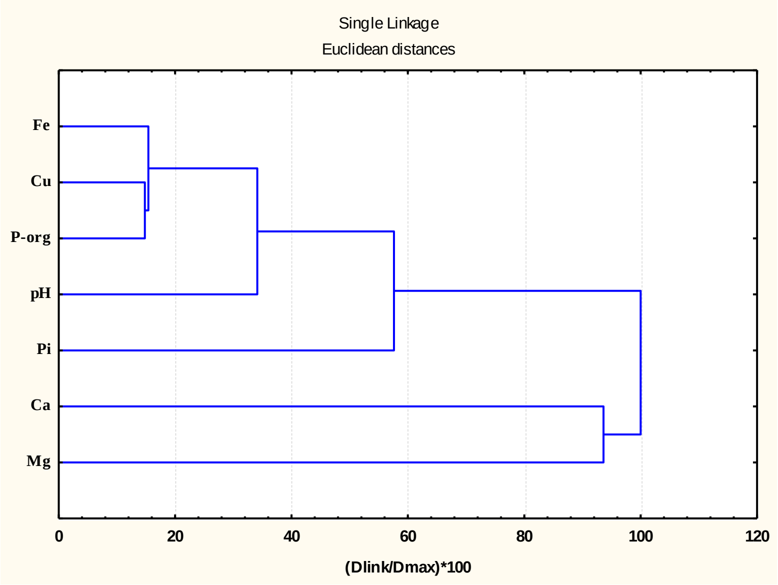

**Figure 1 –** Dendrogram of the variables analysed during the soil incubation

In addition to this we can observe $P_i$ and pH, being the former closer to Ca and Mg cluster and the latter more closely related to the Fe, Cu and $P_o$ cluster.

### 3.7 Plant biomass in the pot test

As reported in Table 5, the pot test showed the above ground dry biomass of plant after 56 day of growing was affected by treatment ($P < 0.05$) and the treatment×$S^0$ interaction ($P < 0.05$). Ctrl S- performed the worst aboveground biomass (6.60 g $pot^{-1}$). The unamended control soil showed increasing above ground biomass at increasing sulphur level, these showing 7.91 and 8.75 g $pot^{-1}$ in Ctrl $S_{50}$ and Ctrl $S_{100}$ respectively. Amongst the organic products GW showed the best above ground dry biomass at $S_{50}$ (GW $S_{50}$, 9.14 g $pot^{-1}$), other treatments (GW S- and GW $S_{100}$) attained to lower DW performing 8.15 g $pot^{-1}$ (on average). The other product (BWSC S-) showed 9.08 g $pot^{-1}$ abound ground dry biomass, being this in the same range of Ctrl $S_{100}$. Within BWSC the dry biomass decreased at increasing sulphur level (BWSC $S_{50}$ and BWSC $S_{100}$), attaining to 8.30 g $pot^{-1}$ (on average). At last P-chem showed intermediate dry biomass of the aboveground tissue, attaining to 7.83 g $pot^{-1}$, regardless of sulphur treatment. Also the root biomass was affected by treatment ($P < 0.001$), and treatment×$S^0$ interaction ($P < 0.001$). In this frame control soil showed the same pattern registered about the aboveground tissue, showing increasing root biomass at sulphur level increase (1.74 vs. 2.71 g $pot^{-1}$ in S- and $S_{100}$). Oppositely GW showed decreasing root biomass at increasing sulphur level from S- to $S_{100}$ (2.74 vs. 2.36 g $pot^{-1}$), while the other product (BWSC) performed the best regardless of $S^0$ (2.77 g $pot^{-1}$, on average). Root biomass in P-chem mimicked GW on average (2.55 vs. 2.54 g $pot^{-1}$) attaining to the best dry weight at $S_{50}$ (2.72 g $pot^{-1}$).

**Table 5 –** Dry biomass, phosphorus and iron content of the above ground plant tissue and root after 56 days of pot cultivation.

| **Treatment** | $\mathbf{S^0}$ | **DW (g)** | | | **P (mg g$^{-1}$)** | | **Fe (mg g$^{-1}$)** | |
|---|---|---|---|---|---|---|---|---|
| | | **Above ground** | **Root** | **Sum** | **Above ground** | **Root** | **Above ground** | **Root** |
| **Control** | **0** | 6.60 b | 1.74 b | 8.34 b | 0.96 b | 1.11 | 0.06 ab | 2.03 b |
| | **1** | 7.91 ab | 2.26 ab | 10.17 ab | 1.06 b | 1.24 | 0.07 a | 2.61 b |
| | **2** | 8.75 a | 2.71 a | 11.46 a | 0.97 b | 1.06 | 0.05 cd | 3.56 b |
| | ***Average*** | ***7.75*** | ***2.23*** | ***9.99*** | ***1.00*** | ***1.14*** | ***0.06*** | ***2.73*** |
| **GW** | **0** | 8.27 ab | 2.74 a | 11.02 a | 1.07 ab | 1.18 | 0.04 d | 3.73 b |
| | **1** | 9.14 a | 2.51 a | 11.65 a | 1.12 ab | 1.21 | 0.04 d | 2.75 b |
| | **2** | 8.02 ab | 2.36 ab | 10.38 ab | 1.22 ab | 1.30 | 0.04 d | 2.82 b |
| | ***Average*** | ***8.48*** | ***2.54*** | ***11.02*** | ***1.14*** | ***1.23*** | ***0.04*** | ***3.10*** |
| **BWSC** | **0** | 9.08 a | 2.77 a | 11.85 a | 0.95 b | 1.42 | 0.05 cd | 3.85 a |
| | **1** | 8.01 ab | 2.80 a | 10.81 a | 1.04 b | 1.26 | 0.06 ab | 4.43 a |
| | **2** | 8.58 ab | 2.73 a | 11.30 a | 1.07 b | 1.15 | 0.05 cd | 5.05 a |
| | ***Average*** | ***8.56*** | ***2.77*** | ***11.32*** | ***1.02*** | ***1.28*** | ***0.05*** | ***4.44*** |
| **P-Chem** | **0** | 7.86 ab | 2.59 ab | 10.45 ab | 1.22 a | 1.18 | 0.06 ab | 3.67 a |
| | **1** | 8.04 ab | 2.72 a | 10.76 a | 1.16 a | 1.30 | 0.05 cd | 3.93 a |
| | **2** | 7.59 ab | 2.32 ab | 9.91 ab | 1.16 a | 1.44 | 0.04 cd | 4.04 a |
| | ***Average*** | ***7.83*** | ***2.55*** | ***10.37*** | ***1.18*** | ***1.23*** | ***0.05*** | ***3.88*** |
| **Treatment** | | * | *** | ** | * | ns | *** | *** |
| $\mathbf{S^0}$ | | ns | ns | ns | ns | ns | * | ns |
| **Treatment × $\mathbf{S^0}$** | | * | *** | *** | ns | ns | ns | ns |

The sum of aboveground and root biomass showed to be also affected by treatment ($P < 0.01$) and by the treatment×$S^0$ interaction ($P < 0.001$). Control soil showed the lowest dry biomass (9.99 g pot$^{-1}$, on average), showing the best at the highest sulphur level (Ctrl $S_{100}$, 11.46 g pot$^{-1}$). Amongst the organic products GW performed the best at S- and $S_{50}$ (11.02 vs. 11.65 g pot$^{-1}$), showing decreasing biomass at $S_{100}$ (10.38 g pot$^{-1}$), while BWSC attained to 11.32 g pot$^{-1}$ (on average), regardless of the sulphur application. The chemical P source (P-chem) attained to intermediate total dry biomass (10.37 g pot$^{-1}$), ranging between control soil (9.99 g pot$^{-1}$, on average) and both composts (11.17 g pot$^{-1}$, on average).

3.7.1 Phosphorus and iron content in plant aboveground tissue and root

Table 5 shows the P content of the aboveground tissue was affected only by the treatment ($P < 0.05$). In this frame control soil and BWSC showed the lowest P content (1.01 mg $g^{-1}$, on average). The other compost (GW) showed increasing P content at sulphur level increase; this compost attained to 1.14 mg P $g^{-1}$ on average, being this in between control soil and the chemical P source, at the highest P in the aboveground tissues (P-chem, 1.18 mg $g^{-1}$, on average). The root P content had no differences regardless of fertilization and $S^0$ application. On the other hand the Fe content of the aboveground tissue resulted affected by both treatment ($P < 0.001$) and $S^0$ ($P < 0.05$). The aboveground tissue from control soil showed 0.06 mg Fe $g^{-1}$ (on average), performing the best at $S_{50}$ (0.07 mg $g^{-1}$). With respect to the control soil, BWSC showed lower Fe content (0.05 mg $g^{-1}$, on average), mimicking control soil pattern with the highest Fe at $S_{50}$ (0.06 mg $g^{-1}$). The above ground tissue from GW showed the lowest Fe, regardless of sulphur application (0.04 mg $g^{-1}$), being this lower than both BWSC and control soil. At last aboveground tissue from P-chem showed 0.05 mg Fe $g^{-1}$, with decreasing trend at increasing sulphur (0.06 vs. 0.04 mg $g^{-1}$). On the contrary the root Fe content resulted affected only by the treatment ($P < 0.001$). This was the lowest in control soil and GW (2.73 vs. 3.10 mg $g^{-1}$). While the other compost (BWSC) showed the highest Fe (4.44 mg $g^{-1}$), in the same range of P-chem (3.88 mg $g^{-1}$).

3.7.2. Phosphorus and iron uptake in plant aboveground tissue and root

The P uptake of the above ground tissue, root and their sum is reported in Figure 2, beside to the Fe uptake. From this figure we can see aboveground tissue from Ctrl S- performed the worst (6.35 mg $pot^{-1}$), GW S- and BWSC S- attained to similar results (8.79 vs. 8.59 mg $pot^{-1}$), being these very close to P-chem S- (9.57 mg $pot^{-1}$).

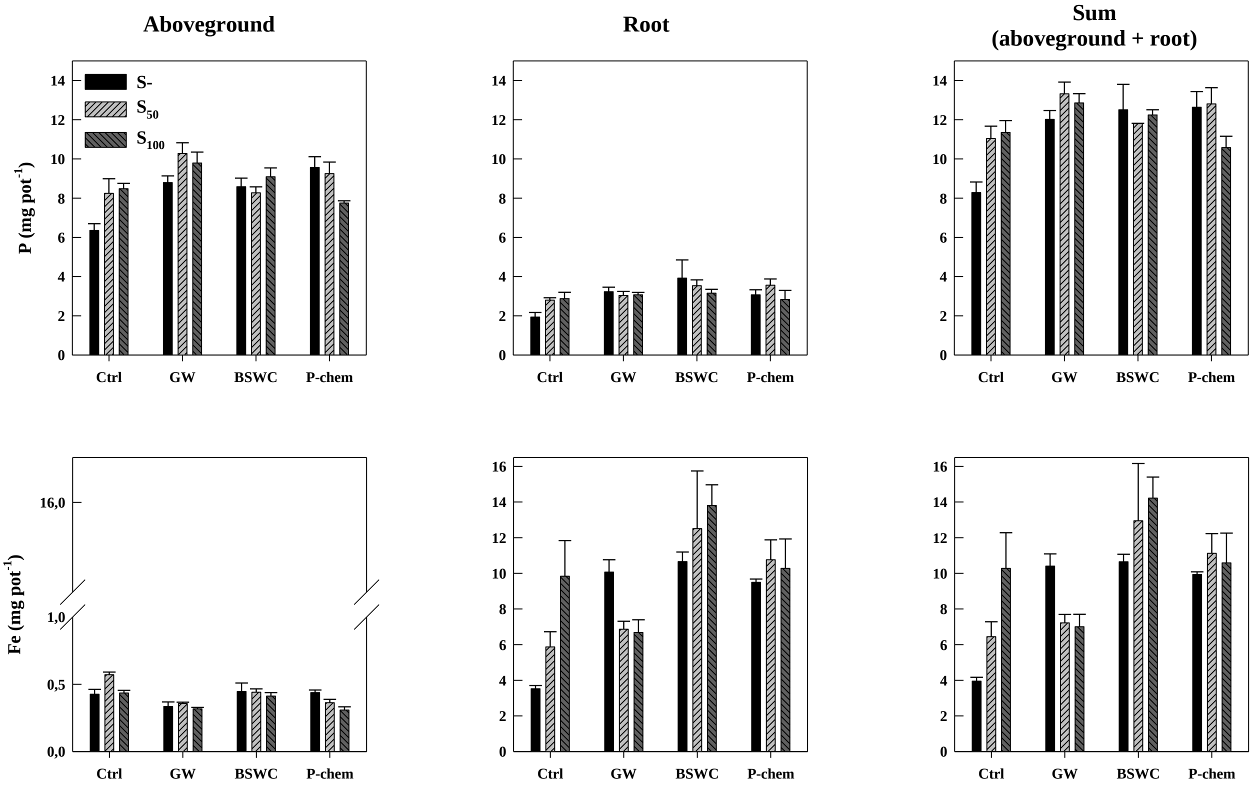

**Figure 2 –** P and Fe uptake in the aboveground tissue, root and total uptake in maize after 56 days of pot cultivation

The root uptake showed control soil S- performed the worst (1.94 mg pot$^{-1}$), GW S- and BWSC S- attained to 3.23 and 3.92 mg pot$^{-1}$, very close to P-chem S- (3.07 mg pot$^{-1}$). The total P uptake (mg pot$^{-1}$) was so the lowest in Ctrl S- (8.29)< GW S- (12.02)< BWSC S- (12.51) ≤P-chem S- (12.63). The $S^0$ utilization attained to different outcomes between the treatments, this was very efficient in control soil attaining to ≈11 mg pot$^{-1}$ on average from both sulphur levels. $S^0$ resulted efficient at both level also on GW (13.3 and 12.9 mg pot$^{-1}$), while this performed negatively in combination with MWSC (12.02 mg pot$^{-1}$ on average) and P-chem (11.69 mg pot$^{-1}$). The Fe uptake was similar in the aboveground tissue from all the treatment regardless of sulphur treatment being at 0.40 mg pot$^{-1}$ on average, only Ctrl $S_{50}$ attained to higher values (0.60 mg pot$^{-1}$). On the contrary the root showed very different Fe uptake: this was detected at 3.52 mg pot$^{-1}$ in Ctrl S- and increased up to 5.87 and 9.84 mg pot$^{-1}$ in Ctrl $S_{50}$ and Ctrl $S_{100}$. GW S- attained to 10.07 mg pot$^{-1}$ showing decreasing Fe uptake at increasing $S^0$ (6.86 vs. 6.68 mg pot$^{-1}$). BWSC S- showed 10.07 mg pot$^{-1}$, performing increasing Fe at the sulphur increase (12.51 vs. 13.81 mg pot$^{-1}$), being this similar to P-chem: 9.50 mg pot$^{-1}$ in S-, 10.76 and 10.28 in $S_{50}$ and $S_{100}$ respectively.

## 4. Discussion

### 4.1 Characteristics of composts

The tested organic products showed the typical characteristics of green waste compost and of a bio-waste, sewage sludge and green waste compost. In this frame GW had the lowest pH and EC. These features besides to the higher C and the lower N clearly showed the different raw materials utilized for GW and BWSC deeply affected their final characteristics. It is widely reported in literature that green waste composts have higher carbon and lower nitrogen content with respect to bio-waste and sewage sludge- based compost, being this features derived from the higher ligno-cellulosic material in green compost and to the higher OM mineralization following the digestion process commonly applied to sewage sludge [22]. Besides to this BWSC showed also higher pH and EC, also these features deriving from the utilization of waste with higher content of soluble salts [23]. Regardless of their origin, both composts showed high stabilization level, being the OUR below 15 mmol $O_2$ kg$^{-1}$ VS h$^{-1}$, thus clustering both products as stable and suitable for safe utilization in soil as suggested by Veeken et al. [24]. Beside to the main characteristics the compared composts showed appreciable differences in the main elements contents. GW showed 30% lower P with respect to BWSC (2.94 vs. 4.32 mg g$^{-1}$). GW showed also lower Ca, Fe and Al being these elements 20-30% lower to what showed by BWSC. Also these features are commonly reported in literature, since sewage sludge are the main source of the abovementioned elements [25]. Regardless of these features both composts showed similar ratio between elements, being Ca:P ≈10; Fe:P ≈3, Al:P ≈4 and Mg:P ≈2.

### 4.2. Phosphorus fractionation

The compared composts showed very different outcomes following the sequential chemical extraction. GW showed

32% labile P ($H_2O$ + $NaHCO_3$), almost doubling MWSC. The greatest difference was registered in the water soluble P, being this in GW almost three times higher than BWSC (13 vs. 5%). This trait is commonly reported for composts having sewage sludge in their mixture [23]. Beside to the composting process itself, which reduce the water soluble P (Eneji et al., 2003) [26], also the flocculating agents (Fe and Al salts) adopted during the sewage sludge processing for P precipitation, deeply decrease the solubility of P in water from this kind of materials (He et al., 2010) [27]. Water soluble P is reported as rapidly utilizable by plants being this trait very important for plant nutrition, showing at the same time potentially leaching risks [28; 3], this issue is further discussed later. The following step of sequential extraction showed the bicarbonate extractable P was found at about 20% (of extractable P) in GW, being this 50% higher than BWSC. The $NaHCO_3$ P is recognized to be weakly sorbed on Ca compounds being this potentially available in the short-middle term for plant [17]. In this frame the lower pH in GW can have reduced fixation on Ca compounds thus increasing the P extractability in $NaHCO_3$. Then the alkali extractable P was found at similar level in both composts, this representing about 15% of extractable P. This fraction is derived from the metal-bound P, and from the phosphorus bound to organic matter. This fraction is recognized to become available for plant in the long term [17]. This issue is further discussed in the other section of the article in which is investigated the effect of Fe on P availability for plants. At last we found that also the sparingly soluble P (HCl-P) showed notably high differences, this fraction represented 50% of extractable P in GW, attaining to ≈70% in BWSC. This fraction is considered fixed on Ca compounds and very hardly available for plants in a calcareous soil (He et al., 2010) [25]. In this frame the similar Ca:P ratio of both composts (Ca:P ≈10), can suggest the common tendency of both GW and BWSC to fix P in this fraction. In literature a Ca:P ratio >2 is considered favourable to the P fixation on Ca [29], the different P extractability from this fraction can be due to the lower pH registered in GW in comparison to BWSC (7.74 vs. 8.35), which can have affected this trait. This features are more deeply discussed later in the pot test.

### 4.3 Soil pH during the soil incubation

The selected soil during the incubation showed the typical calcareous soil pH pattern, showing fairly constant mean values in time (≈7.60), being this environment not favourable to the P solubility [5]. The utilization of elemental sulphur decreased the pH in unamended soil, being this reduced down to 7.25 and 6.87 in $S_{50}$ and $S_{100}$. Similar results were reported by Kaplan and Orman [11], testing the efficiency of $S^0$ on the pH variation in a Turkish calcareous soil. The authors reported limited variation, corresponding to 0.5 pH units, maximum. They utilized 500-1500 kg of $S^0$ $ha^{-1}$ being this values in the lower range of what we adopted in our experiment (1365-2730 kg $ha^{-1}$). At the same time they utilized a soil containing about 40% $CaCO_3$, almost five times higher than the soil we utilized ($CaCO_3$, 8.5%). Both these factors varied the ratio between $S^0$:$CaCO_3$ and this can have affected the pH variation, attaining to different outcomes. With respect to the control soil at the beginning of the incubation (pH, 7.47), the utilization of both GW and BWSC slightly increased the soil pH (7.47 vs. 7.51, on average), then showing very similar course in time. On the whole the addition of $S^0$ reduced the pH of about 0.3 and 0.4 units at the low ($S_{50}$) and at the high level ($S_{100}$), being this variation reduced in comparison to what detected in control soil, thus suggesting a buffering effect due to the compost addition. In GW the higher S level ($S_{100}$) induced a long lasting pH reduction, longer respect to what showed by $S_{50}$ (2 vs. 4 weeks), being this more evident in BWSC (6 vs. 2 weeks). The utilization of $S^0$ in combination with P-Chem mimicked the control soil pH outcomes. In literature is widely reported the addition of organic matter to the soils treated with $S^0$ increase the SOB bacteria activity [9-10]; in this light the utilization of composts can provide the addition of organic carbon which can be useful to increase the SOB activity inducing further pH decrease. In this frame the utilization of recycled organic matter as C source was expected to vary significantly the pH. This effect was not clear in our tests, this was probably due to the very high stability of the tested products, poor of readily available carbon, besides to the high buffering capacity of the selected soil and of the added composts. The organic products we utilized in fact showed sub-alkaline and alkaline pH (7.74-8.33), besides to important amount of Ca. These factors can have affected the pH variation in the tested conditions.

### 4.4. Inorganic and organic P release in the soil incubation

In our experiment the inorganic P from control soil (Ctrl S-) showed the typical pattern from a calcareous soil as described in literature, showing the P decreasing following soil fixation [5]. In unamended control soil the utilization of elemental sulphur slightly increased the extractable P, especially in the central part of the incubation corresponding to the more evident pH decrease, this corresponded to 5-10% increases of the potentially available inorganic P. On the other hand the utilization of both GW and BWSC (without sulphur addition) strongly increased the initial inorganic extractable P with respect to unamended soil (+50 and +30%). This feature was in agreement to what showed by SCE in which GW showed higher labile P in comparison to BWSC (≈+50%). In this frame the soil incubation showed the utilization of $S^0$ reduced the soil P fixation from GW during the incubation, performing both GW $S_{50}$ and GW $S_{100}$ higher inorganic P in the central part of the incubation. Oppositely the utilization of BWSC attained to lower $P_i$ accordingly to the SCE. As previously reported from the SCE compost from bio-waste and sewage sludge (BWSC) had higher sparingly soluble P, this fraction which is fixed to the Ca compounds in composts is very resistant to decomposition. On the contrary GW showed higher $NaHCO_3$ extractable P; this fraction is recognized to be weakly sorbed on Ca compounds, slight pH variation can increase P solubility from this fraction. This is the reason of the different response to the $S^0$ treatment from the different compost very likely. The chemical P source (P-Chem) confirmed the great fixing capacity of soil, showing 50% reduction of extractable inorganic P in the firsts two weeks. Also the chemical reference showed limited effects following $S^0$ utilization, by reducing the P fixation attaining to +15% inorganic P with respect to control soil (on average). Oppositely to what assessed for inorganic P, the labile organic P was found at very low level (almost undetectable) at the incubation start, showing $P_o$ an increasing trend in the first two weeks of incubation. Further decrease in the following stages was then detected, being this fraction mineralized very likely. Organic P extracted form soil is generally reported in literature as potentially mineralizable, this is generally reported of microbial origin [30]. Few are the information are available on this topic following the utilization of composts as fertilizer. It is so possible the higher $P_o$ we found in our experiment in soil treated with GW and BWSC in comparison to what found in unamended control can derive from the microbial decomposition of the added OM. It must be noticed that many are the research dealing with the robustness of $P_o$ assessment in soils. It is widely recognized the measurement of total P by ICP account for all the inorganic P forms (polyphosphate, pyrophosphate ecc.); this measure can be affected also by the complexes formed by P with inorganic polyphosphates and humic (or humic-like) substances, in this light the assessment of “organic” P by difference with the $PO_4$-P determined via the molybdenum blue reaction can overestimate the current organic P [30]. This can be the reason of the overestimation of “organic” P in soil treated with P-chem. It appears however very informative the assessment of $P_o$ which can give an insight of the complex reactions occurring in soil incubation with the different composts. Organic P is recognized to be often linked to the Fe and Al compounds [17], this feature appear to be very important following the utilization in soil of such organic products; in the following section their release is analysed together for a whole comprehension.

### 4.5 Relationships between factors affecting P release in soil during the incubation

As previously reported during the soil incubation we have assessed the course of $P_i$ and labile $P_o$ besides to the course of Ca, Mg, Fe Al and Cu which are recognized to control the P solubility in soil [17; 27]. The data showed that Al was not detectable in the examined extracts so this element was not considered in the following statistical analysis. As reported in the results section the different composts showed similar labile $P_o$ throughout incubation, besides to similar Ca and Mg. On the contrary the different organic products attained to varying extractable Cu, and especially Fe. Many are the researches showing the relationships between $P_o$ and Fe in this type of products, in this frame it is widely recognized that OM play a key role by the formation of links between the above cited elements [17-31]. On this topic Provenzano et al. [31], proved the role of Fe in the formation of Fe-OM complexes in municipal sewage sludge compost, via fluorescence analysis. From our incubation study it appears therefore the release of labile $P_o$ was related to the release of Fe, while the plant P uptake showed an opposite pattern. As better described below we found very high Fe concentration in the root of plants cultivated on soil treated with BWSC. In this treatment the P uptake was lower than plant grown in the soil treated with GW, and in the same range of plants grown in control soil. This feature was more evident in the treatment with $S^0$. The study about P solubility of P are very complexes [30-32]; the solubility of P is dependent by many factors, a part the pH, also the concentration in solution of other cations (such as Ca) play a key role [32]. This systems results also more puzzlingly in the presence of organic P and its further possible mineralization. However Jackman and Black [32] proved the solubility of some organic P forms bound to Fe (ferric phytate) was strongly affected by the Fe:P ratio and by the pH of the solution. They proved at Fe:P ratio of 3.75 the P solubility was negligible at pH ranging between 2 and 7. In their study the P (from ferric phytate) became available at pH >7. What appears therefore from our study is the mineralization of organic P, which resulted not available to plant due to low pH condition induced by $S^0$ treatment thus inducing the subsequent precipitation of inorganic Fe-P complexes. The soil test in fact showed a small increase in the extractability of labile-P following the pH increases occurred at the last stage of the soil test.

### 4.6 Plant pot test

As reported in literature composts have been widely utilized as soil amendments, whit the aim to increase the long-term fertility of agricultural soil [33]. In this frame these products have been extensively investigated for their capacity to increase the biological activity of soils besides to their capacity to furnish nutrients, mainly nitrogen. Less studied is their potential nutrient capacity for P, especially in the short term. In literature the study of the inherent characteristics of composts suggests the imbalance of their nutrients content, having generally greater P with respect to the plant requests [34], being the plant P uptake regulated by the N availability in such conditions. On the other hand composts can be utilized as basal dressing fertilization, to be then coupled to chemical fertilizers, mainly N [33; 35], this approach can deeply affect the plant P uptake [36]. In this frame the pot test we run ensured non-limiting conditions for both N and K, stressing the different plant P uptake from the compared treatments. The pot test showed the utilization of composts increased by ≈12% (on average) the total dry biomass with respect to the control soil in the short period (56 days) of cultivation, resulting both the compared organic products (GW and BWSC), in the same range of P-chem. These result are in agreement to what reported by Eghball and Power [37], testing various type of composts on maize. The authors tested the crop performance in a longer period during a field trial so the results are not fully comparable with ours. Pot test with maize are generally utilized to assess heavy metals uptake [38], however operating in well controlled condition such the condition of our experiment can reduce the environmental factors and allow to assess also the root biomass beside to the root elements uptake. The pot test revealed to a deeper insight the utilization of $S^0$ attained the best outcomes in the unamended soil in which the total dry biomass increased by ≈20 and 40% at the lower and the higher $S^0$ level ($S_{50}$ and $S_{100}$). On the contrary the utilization of $S^0$ coupled with both GW and BWSC attained to a very modest biomass increase. This results are in agreement with the lower available P from control soil in comparison to the soil amended with composts (8 vs. 12 mg $kg^{-1}$), being the P level in unamended soil limiting for plant growth. These findings are proved by the plant P uptake, in this frame control soil performed +30 and + 50% P uptake following the utilization of $S^0$ at the low and the high level (Ctrl $S_{50}$; Ctrl $S_{100}$) in comparison to Ctrl S-. The acidifying action of $S^0$

resulted highly efficient on the plant P availability in control soil, this issue is discussed below.

### 4.6.1 Plant phosphorus and iron uptake

The plant P uptake following the utilization of the different composts was similar in GW and BWSC (12.7 vs. 12.2 mg pot$^{-1}$), corresponding to 12.4 and 14.1% of apparent P recovery with respect to the total applied P (30 mg kg$^{-1}$), being these values within the range reported from this kind of OM source, especially considered in the short term [25-2]. The registered P uptake are very close to what detected in P-Chem (14.5%), attaining GW and BWSC to 89 and 86% relative efficiency with respect to the chemical P source. Despite the great variability of data about P uptake following the utilization of composts, also this values are comprise to what reported in literature for this kind of products [25]. To a deeper insight very different results were registered in pot test at increasing $S^0$. In this frame GW still gained (modest) positive outcomes, while BWSC showed decreasing P uptake. These results were related to the intense accumulation of Fe in the root from the treatment with BWSC, which almost doubled the Fe content registered in control soil. The data from this study showed during the soil incubation the unamended soil performed very low pH at the higher sulphur application (pH, 6.87 at $S_{100}$), this resulting in higher potentially available $P_i$. Moreover unamended soil showed modest Fe increase in solution following sulphur addition, attaining also to the lower Fe accumulation in the plant root. It is widely recognized the utilization of acidifying agent in calcareous soils is generally favourable to the P availability by reducing the fixation of P with the soil calcareous compounds, thus mimicking the acidification operated by root [40], this has also positive effect on Fe availability [5]. On the other hand it is also recognized that beside soil pH, also Al and Fe solubility strongly affect P solubility, in this frame high level of soluble Fe in soil generally correspond to lower available P, especially to pH <7-8 [38-40]. This was in agreement with the Fe content determined in soil following the utilization of the different composts, being the extractable Fe in BWSC almost double in comparison to control soil and GW. Within this topic the formation of different type of Ca-phosphates has been proved in neutral and calcareous soils (in presence of calcite), while fewer information are available about the formation of Fe and Al phosphates in acid soil [40]. Martin et al. [41] observed Fe-phosphates particles when reacting P ions with an iron oxide (goethite). While Rodier and Robert [42] investigated P-rich particles by means of electron microscopy in heavily fertilized soils, evidencing those particles were made of P and either Fe, Al or Ca. In this light many are the study done on the soil behaviour of both P and Fe, while fewer are the literature information on the relationships between P availability and Fe deposition in root. On this topic Mathan and Amberger [39] proved the reduction of P uptake in maize following the addition of increasing amount of Fe (as Fe-EDTA). They also showed a strong accumulation of Fe in root, claiming the precipitation of iron phosphate which reduced the whole P availability, which is what occurred in our experiment very likely.

## 5. Conclusion

The facing P scarcity requires the rational re-utilization of alternative P sources for plant nutrition like composts. In this frame the coupled utilization of composts and natural acidifying agents such as elemental sulphur can be useful to maximize the P mobility in soil and the following plant uptake. In this work we proved the utilization of both green waste- compost and of bio-waste-, sewage sludge- and green waste compost ensured enough P for the first stage of corn growth. The pot test confirmed both the organic products performed very similar to the chemical P reference in a nitrogen non limiting environment showing that a basal dressing with compost coupled with chemical N fertilization can substitute the chemical P fertilization, in the short term. Beside to the positive action of elemental sulphur on the mobilization of native soil P, the utilization of these kind of acidifying agent proved to increase the P uptake only from the green waste compost, characterized by low extractable Fe in soil. In the end we can conclude that composts can be valuable P fertilizer, and we can also conclude that the pH reduction induced by $S^0$ is a valuable strategy to increase plant P uptake only in unamended soil or in soil fertilized with compost which ensure limited amount of extractable Fe. Further investigation about the role of Fe on the limited P uptake in maize is needed in the light to ensure long lasting available P from composts and to verify the complete substitution of chemical P fertilization.

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**Supplementary material**

**Table 5S -** Concentration of the $NaHCO_3$-extractable Fe, Cu, Ca and Mg during the soil incubation of the compared products.

| | | **Fe** | | | | **Cu** | | | | **Ca** | | | | **Mg** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Treatment** | **Time** | **S-** | **$S_{50}$** | **$S_{100}$** | Average | **S-** | **$S_{50}$** | **$S_{100}$** | Average | **S-** | **$S_{50}$** | **$S_{100}$** | Average | **S-** | **$S_{50}$** | **$S_{100}$** | Average |
| **Control** | **0** | 2.0 | 2.2 | 2.7 | ***2.3*** | 0.53 | 0.60 | 0.60 | ***0.58*** | 39 | 38 | 40 | ***39*** | 23 | 23 | 23 | ***23*** |
| | **14** | 2.1 | 2.1 | 2.2 | ***2.1*** | 0.59 | 0.61 | 0.63 | ***0.61*** | 42 | 39 | 39 | ***40*** | 25 | 24 | 24 | ***24*** |
| | **28** | 2.1 | 2.6 | 2.3 | ***2.3*** | 0.61 | 0.62 | 0.64 | ***0.62*** | 30 | 43 | 34 | ***35*** | 25 | 25 | 24 | ***25*** |
| | **42** | 1.8 | 1.8 | 2.3 | ***2.0*** | 0.61 | 0.58 | 0.61 | ***0.60*** | 35 | 34 | 33 | ***34*** | 23 | 23 | 23 | ***23*** |
| | **56** | 2.2 | 3.3 | 3.7 | ***3.1*** | 0.71 | 0.71 | 0.73 | ***0.72*** | 33 | 29 | 33 | ***32*** | 22 | 22 | 24 | ***23*** |
| | ***Average*** | ***2.0*** | ***2.4*** | ***2.6*** | | ***0.61*** | ***0.62*** | ***0.64*** | | ***36*** | ***36*** | ***36*** | | ***23*** | ***23*** | ***24*** | |
| **GW** | **0** | 2.8 | 3.1 | 2.5 | ***2.8*** | 0.73 | 0.70 | 0.65 | ***0.69*** | 41 | 45 | 41 | ***42*** | 29 | 29 | 28 | ***29*** |
| | **14** | 2.8 | 2.3 | 2.8 | ***2.6*** | 0.63 | 0.63 | 0.65 | ***0.64*** | 41 | 38 | 38 | ***39*** | 29 | 29 | 29 | ***29*** |
| | **28** | 2.6 | 2.6 | 2.4 | ***2.5*** | 0.63 | 0.64 | 0.67 | ***0.65*** | 42 | 37 | 32 | ***37*** | 28 | 27 | 27 | ***27*** |
| | **42** | 2.5 | 2.6 | 3.2 | ***2.8*** | 0.68 | 0.73 | 0.72 | ***0.71*** | 34 | 33 | 31 | ***32*** | 25 | 26 | 27 | ***26*** |
| | **56** | 2.2 | 2.3 | 3.5 | ***2.7*** | 0.78 | 0.79 | 0.86 | ***0.81*** | 35 | 32 | 32 | ***33*** | 26 | 26 | 27 | ***26*** |
| | ***Average*** | ***2.6*** | ***2.6*** | ***2.9*** | | ***0.69*** | ***0.70*** | ***0.71*** | | ***38*** | ***37*** | ***35*** | | ***27*** | ***27*** | ***28*** | |
| **BWSC** | **0** | 3.7 | 3.7 | 3.4 | ***3.6*** | 1.03 | 1.06 | 0.94 | ***1.01*** | 51 | 46 | 45 | ***47*** | 24 | 28 | 27 | ***26*** |
| | **14** | 3.2 | 3.4 | 3.4 | ***3.3*** | 0.91 | 0.94 | 0.96 | ***0.94*** | 43 | 40 | 43 | ***42*** | 28 | 28 | 29 | ***28*** |
| | **28** | 3.6 | 4.0 | 3.8 | ***3.8*** | 0.99 | 1.01 | 1.03 | ***1.01*** | 41 | 38 | 39 | ***39*** | 27 | 27 | 27 | ***27*** |
| | **42** | 3.8 | 3.5 | 3.7 | ***3.7*** | 1.00 | 0.95 | 1.04 | ***1.00*** | 36 | 40 | 38 | ***38*** | 25 | 27 | 28 | ***27*** |
| | **56** | 5.1 | 4.2 | 4.3 | ***4.5*** | 1.08 | 1.07 | 1.13 | ***1.09*** | 35 | 33 | 34 | ***34*** | 26 | 25 | 26 | ***26*** |
| | ***Average*** | ***3.9*** | ***3.8*** | ***3.7*** | | ***1.00*** | ***1.01*** | ***1.02*** | | ***41*** | ***39*** | ***40*** | | ***26*** | ***27*** | ***27*** | |
| **P-chem** | **0** | 2.3 | 2.4 | 2.5 | ***2.4*** | 0.58 | 0.58 | 0.64 | ***0.60*** | 43 | 42 | 43 | ***44*** | 24 | 24 | 23 | ***24*** |
| | **14** | 2.0 | 2.4 | 2.0 | ***2.1*** | 0.59 | 0.62 | 0.58 | ***0.60*** | 34 | 42 | 34 | ***39*** | 24 | 24 | 26 | ***25*** |
| | **28** | 2.2 | 2.4 | 2.1 | ***2.2*** | 0.60 | 0.65 | 0.59 | ***0.61*** | 36 | 33 | 36 | ***36*** | 23 | 23 | 22 | ***23*** |
| | **42** | 2.6 | 1.8 | 2.4 | ***2.3*** | 0.57 | 0.57 | 0.65 | ***0.60*** | 32 | 30 | 32 | ***33*** | 22 | 22 | 22 | ***22*** |
| | **56** | 2.3 | 2.5 | 1.9 | ***2.2*** | 0.76 | 0.76 | 0.69 | ***0.74*** | 33 | 30 | 33 | ***33*** | 23 | 22 | 22 | ***22*** |
| | ***Average*** | ***2.3*** | ***2.3*** | ***2.2*** | | ***0.62*** | ***0.64*** | ***0.63*** | | ***39*** | ***36*** | ***35*** | | ***24*** | ***23*** | ***23*** | |