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Full Length Research

Selenium accumulation and growth of perennial ryegrass (*Lolium perenne* L.) as affected by pig manure composting

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ABSTRACT: At trace concentrations, selenium (Se) has been shown to exert positive effects on plant growth, but Se essentiality to higher plants remains in doubt. Plants can absorb Se from the soil in inorganic or organic forms, but the cycling and bioavailability of organic Se in the manure-soil-plant system remain to be fully understood. This study investigated the effects of pig manure composting on the growth and Se accumulation in *Lolium perenne* L. (cv. Riikka) at different growth stages. A pot experiment with silica sand amended with Se-enriched mineral fertilizer (NPK-Se), dried, ground pig manure (PM) and pig manure compost (PMC) at 200 mg N kg^{-1} soil was carried out under controlled greenhouse conditions. Addition of NPK-Se, PM and PMC significantly ($p \leq 0.05$) increased dry matter content in the stems and roots, on average, by 28 and 19% respectively. Inorganic (NPK-Se) and organic (PM and PMC) treatments slightly increased net photosynthesis, stomatal conductance, transpiration and leaf area in plants. Inorganic Se (NPK-Se) markedly increased Se content in the shoots, on average, by 35% at all growth stages. Even though Se concentration in the roots was 3-fold higher in pig manure (PM and PMC) fertilized-plants, translocation to the shoots was reduced. Interestingly, Se concentration in the shoots was higher in PMC-plants compared to PM-plants at all growth stages. However, the effect of composting on Se concentration was not significant. Overall, the results indicate that composting improves the fertilizer value of pig manure with possible stimulatory effects on organic-Se mineralization.

Keywords: Agronomic biofortification, bioavailability, mineralization, organic fertilization, organic selenium.

INTRODUCTION

At low concentrations, selenium (Se) is a key component of the antioxidant enzyme glutathione peroxidase (GSH-Px) and also an essential micronutrient for humans, animals and microorganisms. But its essentiality for higher plants remains debated (Rayman, 2000; Hartikainen, 2005; Duntas and Benvenga, 2015). Selenium has been reported to enhance plant growth and tolerance to abiotic stresses (Hartikainen and Xue, 1999; Hawrylak-Nowak, 2009; Yao et al., 2009) as well as, carbohydrate metabolism (Turakainen et al., 2004; Malik et al., 2010; Owusu-Sekyere et al., 2013). Higher plants differ in their Se uptake and the levels depend on the plants requirements and soil Se concentrations (Hartikainen, 2005; Duntas and Benvenga, 2015; Söderlund et al., 2016). In regions with soil Se deficiencies and low dietary Se intake, metabolic diseases in humans and nutritional myopathy in animals have been reported (Rayman, 2000; Alfthan et al., 2015; Söderlund et al., 2016). However, the use of Se-enriched multinutrient fertilizers (agronomic biofortification) has been successful in addressing Se deficiencies in soils and dietary plants in Finland, New Zealand and China over the last three decades (Eurola et al., 1990; Alfthan et al., 2015).

Worldwide, interest in sustainable food and feed production using less mineral (NPK) fertilizers is increasing. This has renewed the interest in using crop residues, on-farm manures and slurries to meet crops nutrient requirements (Jensen, 2013; Provolo et al., 2018). Addition of manures and other organic amendments have been reported to enhance soil aggregate and structure, soil water holding capacity, soil organic matter (SOM) content and serve as renewable source of nitrogen (N) and phosphorus (P) to plants (Edmeades, 2003; Eden et al., 2017). Animal manures and slurries can also be an important source of micronutrients as most livestock feed rations are supplemented with these essential trace elements (Cu, Fe, Zn, B, Se) (Jensen, 2013). For example, pig rations are often supplemented with 0.8 to 1.1 g Na/kg dry matter (DM), 125 to 250 mg Cu/kg DM (Wallace et al., 1960), 20 mg Mn/kg DM, 100 to 150 mg Zn/kg DM (EFSA, 2014) and 0.15 to 0.50 mg Se/kg DM with maximum tolerable level at 4 mg Se/kg feed dry matter (EFSA, 2006) for normal growth and reproduction.

However, there is some concern that the use of untreated animal wastes as fertilizers may introduce pathogens (eggs of parasitic worms, bacteria, viruses, protozoa) into soils and eventually into the food chain (Bicudo and Goyal, 2003; Venglovsky et al., 2018). Also, the continuous long-term application of manures and slurries may result in excessive accumulation of heavy metals in the top soil causing toxicity to some plants and leaching of nutrients into surface and underground water (Provolo et al., 2018). Thus, to reduce these risks and also improve the fertilizer value of animal wastes, eco-friendly waste treatment methods such as anaerobic and aerobic decomposition (composting) are being used in sustainable production systems (Brockmann et al., 2014; Sáez et al., 2017). Several studies have reported that composting enhances soil aggregate and structure, soil water holding capacity and formation of stable soil organic matter (SOM) (Jensen, 2013; Eden et al., 2017). However, to our knowledge, studies on the effects of composting on Se cycling and bioavailability in manures and slurries and subsequent uptake in dietary plants is lacking. The aim of this study was to examine, under controlled conditions, the effects of composting on Se cycling and bioavailability in pig manure, and how well they affect Se accumulation and growth of *Lolium perenne* L. at different growth stages.

MATERIALS AND METHODS

Pig manure compost (PMC)

Pig manure consisting of excreta, wasted feed, straw and wood chips from the pig shed was obtained from fattening pigs in a commercial piggery located in Helsinki (Finland). The pig rations were supplemented with Se-rich protein (fish) meal to meet the recommended Se-requirements (0.2 mg/kg DM) for pigs (MTT, 2004). The manure was collected in plastic containers and stored in the cold at 5°C. It was later mixed with biodegradable plant material (wheat straw) in the ratio of 2:1 and allowed to decompose aerobically for 2 months. The heap was mixed weekly to enhance composting. Subsamples of the pig manure were analyzed at Viljavuuspalvelu Oy, Mikkeli, Finland and the physico-chemical characteristics are described in Table 1.

Experimental design and treatments

Pot experiment with silica sand (grain size 0.1 to 0.6 mm, SP-Minerals Oy, Nilsiän kvartsi, Finland) was conducted in the greenhouse at the Department of Agricultural Sciences, University of Helsinki, Finland (60°13'38" N, 25°10'00" E). The experiment was carried out in a randomized complete block design with four treatments, each replicated four times. The treatments were: (a) mineral (NPK) fertilizer without Se (Control), (b) NPK fertilizer enriched with Na_2SeO_4 (0.0025 mg Se kg^{-1}) (NPK-Se), (c) pig manure (PM), and (d) pig manure compost (PMC). Silica sand is chemically inert and was used in this study to prevent adsorption of Se and other nutrients to soil particles.

Three (3)-L polythene-lined plastic pots were filled with 2 kg of silica sand thoroughly mixed with mineral fertilizer (N:P:K =20:9:12), ground and sieved (2.00 mm) PM and PMC applied at the same rate of 200 mg N kg^{-1} soil. The moisture content of the soil was adjusted to 70 to 80% of water-holding capacity. The pots were covered with black polyethene bags to reduce excessive ammonia (NH_3) volatilization in manure-amended soils. The pots were then incubated at room temperature for eight weeks and water losses exceeding 10% during the incubation period was compensated by addition of distilled water. Soil pH and electrical conductivity (EC) was measured in both deionized water (1:5 H_2O) and 0.01 M calcium chloride ($CaCl_2$) (Sumner, 1994).

Perennial ryegrass (cv. Riikka) seeds were sown (10 seeds per pot) and thinned to four seedlings per pot after germination. Growth conditions in the greenhouse were monitored throughout the experiment and maintained at day/night temperature of at 28/16°C, relative humidity of 70 to 80% and a photoperiod of 16/18 h provided by natural light and fluorescent lamps at a mean photon flux density of 400 µmol photons m^{-2} s^{-1}. Plants were watered 1- to 2 times a day with deionised water (electrical conductivity <1 µS cm^{-1}) as needed to maintain soil moisture level (approximately 60% of water holding capacity) and prevent leaching of nutrients. Plants were harvested at three growth stages: (a) first harvest (6 weeks after germination) at the vegetative stage, (b) second harvest (8 weeks after germination) at the elongation stage, (c) third harvest (11 weeks after germination) at the transition/booting stage, hereafter referred to as H1, H2 and H3, respectively. Gas exchange parameters (net photosynthesis, stomatal conductance and transpiration) of the youngest fully expanded leaf and whole plant leaf area were measured before each harvest using a portable photosynthesis meter (LI-6400, LI-COR, USA) (Long et al., 1996) and leaf area meter (LI-3000, LI-COR, USA) (LI-COR, 2015).

Sampling and analyses

At each harvest, shoots and roots were separated and the roots were carefully washed with deionised water and blotted dry with tissue. The fresh weights (FW) of shoots and roots were measured and the dry weights (DW) of samples also recorded after drying at 70°C for 48 hours (h). Subsamples were milled (Retsch ZM 200, Germany) to fine particle size of 0.5 mm for the analyses of total nitrogen (N) and carbon (C) contents using the Dumas combustion method (Hansen, 1989) and Se contents of plant samples. Crude protein (CP) was calculated by multiplying total N content by coefficient 6.25 (AOAC, 2000).

Selenium analysis

The total Se concentration in plant samples were analyzed by the electrothermal atomic absorption spectrometric method for food samples (Kumpulainen et al., 1983; Ekholm, 1996). Aliquots of the dried and milled plant samples were weighed (0.2 to 0.5 g) in duplicate into wet-digestion tubes. The tubes were incubated overnight in 10 mL of a concentrated acid mixture (HNO_3-$HClO_4$-H_2SO_4, 2.5:1.5:1) at room temperature. The digestion was completed according to a five-step temperature protocol: 30 min at 70°C, 3 h for 120°C, 30 mins for 160°C, 30 min for 190°C and 5 h for 220°C. Selenate was reduced to selenite with dilute HCl (12 %) and extracted using the ammonium pyrrolidine dithiocarbamate-methyl isobutyl ketone (APDC-MIBK) procedure described by Keskinen et al. (2010). The extracts were analyzed in duplicate by ICP-OES (iCPA 6000 Series, Thermo Scientific). Three in-house samples (wheat flour) with known Se concentration were used as standards.

Statistical analysis

Statistical analysis of data was performed using PASW 18 analytical software (SPSS Inc., Chicago, IL, USA). Data was subjected to one-way ANOVA and differences in means compared with Tukey's test at $p \leq 0.05$.

RESULTS

Growth and gas exchange parameters

Inorganic (NPK-Se) and organic (PM and PMC) applications exerted positive effects on plant growth and development. Addition of NPK-Se significantly ($p \leq 0.05$) increased herbage dry matter yield about 14 to 25% compared with control plants. Organic (PM and PMC) applications markedly increased shoot dry matter (DM) content about 18 to 37% compared with control plants (Table 2). Similarly, inorganic (NPK-Se) and organic (PM and PMC) applications also enhanced root DM at the vegetative and booting stages (Table 2).

Table 1. Selected physical and chemical characteristics of manure used in the study (dry weight basis).

Characteristics	Pig manure (PM)	Pig manure compost (PMC)
pH (H_2O) (1:5 v/v)	7.8	6.9
pH ($CaCl_2$)	8.2	7.0
Moisture (%)	73.5	69.2
Organic matter (g kg^{-1})	352.0	368.0
EC (dSm^{-1}) (1:5 v/v)	12.1	10.7
Dry matter (%)	30.3	36.4
Total N (g kg^{-1})	43.9	47.3
Total P (g kg^{-1})	45.2	49.0
Total K (g kg^{-1})	14.6	19.2
Total Ca (g kg^{-1})	39.3	26.5
Humic acids (%)	7.6	9.4
Fulvic acids (%)	5.7	6.3
C/N ratio	12.5	9.8
Fe (%)	1.3	1.2
Zn (mg kg^{-1})	1341.0	1318.0
Cu (mg kg^{-1})	165.1	161.7
Se (mg kg^{-1})	2.7	3.1

Inorganic (NPK-Se) and organic (PM and PMC) applications exerted positive effects on herbage N concentration as reflected by increases in herbage crude protein (CP) contents. However, treatments did not affect shoots C/N ratio (Table 3). Herbage CP content was highest (17.1% DM) at the elongation stage (H2) but the levels decreased slightly (16.5%) at the booting stage (H3). Addition of PM and PMC increased CP content approximately from 16.5 to 18.6% DM at the earlier growth stages (H1 and H2).

Also, NPK-Se and organic (PM and PMC) treatments increased net photosynthesis about 18 to 22% compared with control plants at the earlier growth stages (H1 and H2). In all treatments, measured net photosynthesis was high (15.17 to 16.43 µmol CO_2 m^{-2} s^{-1}) at the elongation growth stage (H2). A similar trend was also observed for measured stomatal conductance and transpiration in these plants (Table 4). Addition of NPK-Se, PM and PMC also exerted positive effects on leaf area at all growth stages. From the vegetative (H1) to booting stage (H3), leaf area increased approximately from 0.41 to 0.84 m^2 in all treated plants compared with the control plants (0.34 to 0.72 m^2) (Table 4).

Se accumulation in plants

As expected, addition of Se-enriched mineral (NPK-Se)

Table 2. Dry weights (DW) (g) of shoots and roots of *Lolium perenne* L. fertilized with NPK without Se (control), Se-enriched NPK fertilizer (NPK-Se), pig manure (PM) and pig manure compost (PMC) at 200 mg N kg^{-1} soil. Plants were sampled at vegetative (H1), elongation (H2) and booting (H3) growth stages.

Treatment	Dry matter yield (g pot^{-1})					
	Vegetative (H1)		Elongation (H2)		Booting (H3)	
	Shoot	Root	Shoot	Root	Shoot	Root
Control	2.55 ± 0.3^d	1.16 ± 0.3^c	6.60 ± 0.3^d	3.73 ± 0.5^a	7.36 ± 0.2^d	3.13 ± 0.2^c
NPK-Se	3.38 ± 0.1^c	1.19 ± 0.0^b	7.69 ± 0.2^c	2.08 ± 0.1^d	9.67 ± 0.3^c	3.73 ± 0.5^b
PM-Se	3.65 ± 0.1^b	1.13 ± 0.1^c	8.09 ± 0.1^b	3.36 ± 0.1^b	10.92 ± 0.3^b	4.59 ± 0.2^a
PMC-Se	3.84 ± 0.0^a	1.37 ± 0.1^a	9.02 ± 0.1^a	3.16 ± 0.2^c	11.73 ± 0.1^a	4.84 ± 0.1^a

Data are means ± SE; n = 4. Values in each column with the same letters are not significantly different at $p \leq 0.05$. Columns are tested separately.

Table 3. Mean herbage C/N ratio and crude protein content (%) of *Lolium perenne* L. fertilized with NPK without Se (control), Se-enriched NPK fertilizer (NPK-Se), pig manure (PM) and pig manure compost (PMC) at 200 mg N kg^{-1} soil. Plants were sampled at vegetative (H1), elongation (H2) and booting (H3) growth stages.

Treatment	H1	H2	H3
C:N ratio			
Control	17.5 ^{a}	17.4 ^{a}	18.1 ^{a}
NPK-Se	17.6 ^{a}	16.7 ^{a}	18.2 ^{a}
PM-Se	16.7 ^{a}	15.5 ^{a}	17.2 ^{a}
PMC-Se	17.1 ^{a}	16.6 ^{a}	18.1 ^{a}
SE	0.55	0.85	0.38
Crude Protein content (%)			
Control	15.4 ^{b}	15.8 ^{c}	16.0 ^{c}
NPK-Se	15.7 ^{b}	17.1 ^{b}	16.5 ^{b}
PM-Se	16.7 ^{a}	18.6 ^{a}	17.6 ^{a}
PMC-Se	16.5 ^{a}	17.7 ^{b}	17.0 ^{b}
SE	0.51	0.72	0.29

Data are means ± SE; n = 4. Values in each column with the same letters are not significantly different at $p \leq 0.05$. Columns are tested separately.

fertilizer had positive effects on Se content in shoots and roots of plants. At the vegetative growth stage, herbage Se content was about 36 to 47% higher in NPK-Se plants compared with PM and PMC-plants (Figure 1). Selenium concentration was highest in the shoots (0.21 µg g^{-1} DM) and roots (0.12 µg g^{-1} DM) of NPK-Se-plants at 6 weeks after germination (H1). But the Se concentration in the shoots and roots decreased with plant growth and was lowest (0.13 µg g^{-1} DM and 0.09 µg g^{-1} DM respectively) in mature plants (H3) (Figure 1). In plants fertilized with pig manure (PM and PMC), Se concentration in the shoots was highest (0.11 µg g^{-1} DM and 0.13 µg g^{-1} DM respectively) at the vegetative stage (H1), after which the concentration decreased. But the differences in the shoot levels were not significant. Interestingly, Se accumulation was 3-fold higher in the roots of PM and PMC-plants compared with NPK-Se plants. Selenium concentration in the roots significantly ($p \leq 0.05$) increased with plant growth in PM-treated (0.36 to 0.48 µg g^{-1} DM) and PMC-treated (0.31 to 0.43 µg g^{-1} DM) plants (Figure 1).

DISCUSSION

Sustainable management practices have tremendous impact on nutrient cycling (mobility, availability and uptake) within the soil-plant ecosystem. The addition of Se-enriched mineral fertilizer (NPK-Se) and pig manure (PM and PMC), in this study, exerted positive effects on plant growth and development as indicated by significant ($p \leq 0.05$) increases in shoots and roots dry matter (DM) yield at all growth stages (Table 2). The results of this study are in agreement with the earlier findings on Se growth-promoting effects in ryegrass (Hartikainen and Xue, 1999), potato (*Solanum tuberosum* L.) (Turakainen et al., 2004), and oilseed rape (*Brassica napus* L.) (Ebrahimi et al.,

Table 4. Net photosynthesis (µmol CO_2 m^{-2} s^{-1}), stomatal conductance (*gs*, mol m^{-2} s^{-1}), transpiration (*E*, mmol m−2 s−1), and leaf area (LA, m^2) of *Lolium perenne* L. fertilized with NPK without Se (control), Se-enriched NPK fertilizer (NPK-Se), pig manure (PM) and pig manure compost (PMC) at 200 mg N kg^{-1} soil. Plants were sampled at vegetative (H1), elongation (H2) and booting (H3) growth stages.

Treatment	H1	H2	H3	H1	H2	H3
	Net photosynthesis (µmol CO_2 m^{-2} s^{-1})			Stomatal conductance (mol m^{-2} s^{-1})		
Control	9.71^{d}	10.69^{d}	8.53^{c}	0.24^{c}	0.36^{d}	0.21^{c}
NPK-Se	12.42^{a}	15.17^{c}	11.36^{a}	0.38^{b}	0.51^{c}	0.31^{b}
PM-Se	11.83^{c}	16.43^{a}	10.52^{b}	0.43^{a}	0.54^{b}	0.34^{a}
PMC-Se	12.22^{b}	15.71^{b}	11.31^{a}	0.41^{a}	0.62^{a}	0.32^{b}
SE	0.19	0.40	0.21	0.01	0.02	0.01
	Transpiration (mmol m^{-2} s^{-1})			Leaf area (m^2)		
Control	2.36^{d}	3.57^{c}	3.28^{d}	0.34^{c}	0.59^{b}	0.72^{d}
NPK-Se	2.51^{c}	3.65^{a}	3.43^{c}	0.43^{a}	0.55^{c}	0.84^{a}
PM-Se	2.63^{a}	3.61^{b}	3.46^{b}	0.41^{b}	0.62^{a}	0.78^{c}
PMC-Se	2.56^{b}	3.54^{d}	3.51^{a}	0.44^{a}	0.58^{b}	0.81^{b}
SE	0.02	0.01	0.02	0.01	0.01	0.01

Data are means ± SE; n = 4. Values in each column with the same letters are not significantly different at $p \leq 0.05$. Columns are tested separately.

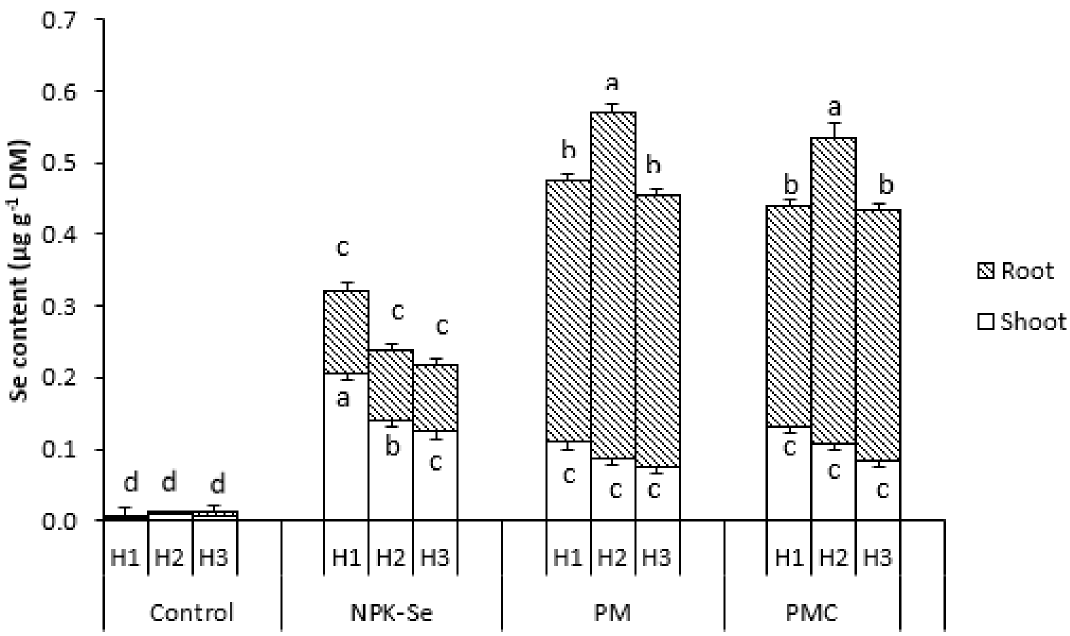

Figure 1. Mean selenium (Se) content (µg g^{-1} DM) of *Lolium perenne* L. fertilized with NPK without Se (Control), Se-enriched NPK fertilizer (NPK-Se), pig manure (PM) and pig manure compost (PMC) at 200 mg N kg^{-1} soil. Plants were sampled at vegetative (H1), elongation (H2) and booting (H3) growth stages. Data are means ± SE; n = 8. Means with different letters in the same plant part (shading) are significantly different at $p \leq 0.05$.

2015). Similarly, other studies have also reported of the positive effects of organic amendments on plant growth and DM yield (Provolo et al., 2018; Kizito et al., 2019). The increased growth and biomass accumulation in the shoots and roots of plants in this study may be explained by the increases in net photosynthesis (Table 4). Thus, the results suggest that photo-assimilates were efficiently used in DM production.

In the present study, NPK-Se and pig manure (PM and PMC) additions exerted positive effects on herbage N (data not shown) and crude protein (CP) contents (Table 3). At the earlier growth stages (H1 and H2), these treatments increased CP content about 2 to 15%. But the effects tended to decrease in mature plants (H3) (Table 3). Nonetheless, the herbage CP content in this study, is in the range (9 to 18%DM) reported by Sanderson and Wedin (1989) and Hoekstra et al. (2008). The relatively low CP content in mature plants (H3) in this study may be attributable to biomass dilution (Table 2) due to increased accumulation of cell wall carbohydrates (Van Soest, 1994). Interestingly, it was also observed that CP content was generally high in pig manure treated plants than in NPK-Se plants (Table 3). Added pig manure provides adequate supply of both inorganic N forms, as well as slowly available organic N forms (Brockmann et al., 2014). Also, the low C/N ratios of PMC and PM (9.8 to 12.5) (Table 1) used in this study can enhance microbial decomposition of soil organic matter (SOM) resulting in increased mineralization of organically-bound N to ammonia (NH_4^+) and release of other essential nutrients for plants uptake. But the chemical composition of pig manure depends on the type and age of the animals, feed, and management system (Sáez et al., 2017; Provolo et al., 2018).

As expected, the addition of NPK-Se had positive effects on Se content in the shoots and roots of plants. At the earlier growth stage (H1), shoot Se content was markedly high in these plants than in pig manure (PM and PMC) and control plants. But, the levels in the shoots and roots tended to decrease with plant growth (Figure 1). This may be explained by biomass dilution due to marked increases in shoots and roots DM (Table 2). Interestingly, Se accumulation was markedly high in the roots of PM and PMC-plants at all growth stages and the translocation to shoots seem restricted (Figure 1). The results in this study are in agreement with previous findings in wheat (*Triticum aestivum* L.) (Eich-Greatorex et al., 2007) and oilseed rape (Ebrahimi et al., 2015) where the translocation of organic-Se from the roots to vegetative parts seemed reduced. Selenium translocation from roots to shoots can be inefficient in ryegrass and other Se non-accumulators (Williams and Mayland, 1992). Other studies also indicate that Se hyperaccumulators and non-accumulators can periodically remobilize Se from shoots tissues to the roots (Galeas et al., 2007; Pilon-Smits and Le Duc, 2009). But Se partitioning in plants is also influenced by plant genotype and developmental stage (Williams and Mayland, 1992; Hartikainen, 2005).

In this study, Se uptake and accumulation in the shoots of plants fertilized with pig manure (PM and PMC) were generally low compared with NPK-Se plants (Figure 1). Although Se mineralization was not directly measured in this study, the increased shoot Se concentration in PMC plants indicate that composting may have enhanced the mineralization of organic-Se to inorganic forms for plant uptake. Eghball et al. (2002) reported that composting enhances the conversion of easily mineralizable N and other nutrients to inorganic forms for plant uptake. However, the effect of organic matter (OM) on Se availability is complex and reportedly double-edged (Supriatin et al., 2015b; Dinh et al., 2017). Earlier findings by Sharma et al. (2011) in wheat and oilseed rape reported of low Se availability in manures with high organic matter content. These authors suggested that Se in manure is immobilized by microbes and reduced to elemental Se or indirectly adsorbed by organo-metals complexes. However, other studies have also reported that, at low pH, low-molecular-weight organic acids (LMWOAs) can inhibit adsorption of Se, and enhance the dissolution and release of immobilized Se into soil solution for plant uptake (Øgaard et al., 2006; Dinh et al., 2017; Dun et al., 2019). Overall, the results show that Se uptake and accumulation in plants is dependent on plant species, developmental stage of the plant, chemical, physical and biological soil properties and processes that control Se speciation and solubility in the soil.

Conclusion

The addition of Se-enriched mineral fertilizer (NPK-Se) and pig manure (PM and PMC) had positive effects on plant growth and development. Fertilization increased dry matter accumulation in shoots and roots of plants, C and N concentrations and crude protein content in plants. These may be attributable to efficient N utilization and partitioning of photoassimilates in plants. Selenium (Se) uptake and accumulation was markedly high in the shoots of NPK-Se plants. Although Se accumulation in the shoots of plants treated with manure was generally low, the results obtained under controlled conditions, suggest increased mineralization of organic-Se in pig manure compost (PMC). However, care should be taken, when inferring these results to field conditions or studies with other organic-Se forms. More studies are needed to fully understand the effects of microbial decomposition and mineralization on organic-Se uptake in plants. Overall, the results clearly show that the use of inorganic Se remains the most effective approach for biofortification purposes. However, the cautious application of pig manure with high Se concentration can be a sustainable strategy to increase Se concentration in Se-deficient soils.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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