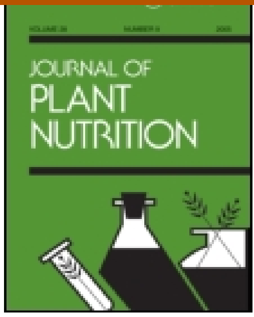

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ORGANIC LETTUCE GROWTH AND NUTRIENT UPTAKE RESPONSE TO LIME, COMPOST AND ROCK PHOSPHATE

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□ *Fertilizer recommendations are needed to increase organic vegetable yields. Thus, organic lettuce growth and nutrient uptake was investigated in a randomized block pot experiment with twelve treatments from the factorial structure of three factors: (i) Gafsa phosphate [0 and 200 kg phosphorus pentoxide (P_2O_5) ha^{-1}], (ii) compost from source separated municipal organic waste (0, 15, and 30 t ha^{-1}) and (iii) limestone [0 and 8 t ha^{-1} calcium carbonate ($CaCO_3$) equivalent]. Lettuce yield increased with compost application and a first order interaction between lime and phosphate was clear because lime partially replaced the need for phosphate. This was explained by the effect of liming on P availability in acid soils. Nitrogen (N), phosphorus (P), and potassium (K) accumulation increased in lettuces produced with compost or phosphate but only the accumulation of N was increased with lime. This compost is recommended to increase nutrient availability for organic lettuce whereas the need for phosphate fertilization may decrease with liming.*

Keywords: compost, fertilizers, nitrogen, nutrient uptake, phosphorus

INTRODUCTION

Lettuce (*Lactuca sativa* L.) is an important horticultural crop in northwest Portugal where it is grown throughout the year in the conventional way, but not often in organic agriculture (OA). To increase the yield of organic lettuce, experimental results are needed to support the organic fertilization recommendations focused on how to provide nutrients in appreciable amounts to achieve high yields without the use of conventional fertilizers.

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Organic agriculture (OA) relies on soil organic matter (OM) to enhance soil nutrient availability, which increases with the application of organic amendments according to their characteristics, application rates and soil conditions (Wong et al., 1999; Flavel and Murphy, 2006; Johnston, et al., 2009; Montemurro, 2010). Composts can improve soil structure and encourage soil biological diversity and activity (Carpenter-Boggs et al., 2000; Yun and Ro, 2009) but vary greatly in their composition, degree of stabilization and ability to release nutrients for plants (Sikora and Szmidt, 2001). However, to successfully manage the cycle of nutrients in the soil to match crop needs the rates of mineralization of organic amendments should be estimated, likewise the influence they exert on soil processes and properties (Ambus et al. 2002; Gabrielle et al., 2004). A limiting factor in the use of excessive amounts of composts, particularly when they are not completely matured, could result from toxicity caused by high contents of salts or ammonium (NH_4^+), or soil nitrogen (N) immobilization (Brito, 2001).

One of the challenges for sustainable use of composts is that compost application to provide N may over supply phosphorus (P). This is because the N/P ratio of composts is significantly smaller than the N/P uptake ratio of most crops (Eghball, 2002). However, P is relatively immobile in the soil profile and its availability in soil solution can be greatly reduced by the presence of OM and the presence of calcium and magnesium carbonates (Sample et al., 1980). If needed, the natural rock phosphates can be as effective as soluble phosphates (Corrêa, et al., 2005), but their efficiency depends on the crop, soil type, the rate of application, and on soil pH. The ideal soil pH for lettuce growth in mineral soils is between values of 6 and 6.8 (Maynard and Hochmuth, 1997). A low pH value reduces the solubility of P due to precipitation of aluminum (Al), iron (Fe), and manganese (Mn) phosphates (Jiao et al., 2008; Devau et al., 2009), and decreases the rates of OM mineralization because it harms the soil microbial activity (Lear, et al., 2004). Liming may be recommended for growing lettuce in acid soils and there are several alkaline amendments allowed for OA. However, the effect of lime should be evaluated in combination with the use of other certified fertilizers. Therefore, the objective of this work was to assess lettuce growth and nutrient uptake and partitioning, in response to lime, compost and rock phosphate, and the interactions between these fertilizers to improve organic lettuce fertilization.

MATERIALS AND METHODS

A randomized block designed pot experiment was set up with lettuce (*Lactuca sativa* L.) inside a greenhouse (unheated) located in Ponte de Lima, Portugal (41° 47′ 30″ N, 8° 32′ 24″ W and 50 m high), according to organic agriculture regulations (EC Reg. 834/2007). Each of four blocks included 12 treatments resulting from the factorial structure of the following three factors: (i) Gafsa natural rock phosphate with two levels [0 and 200 kg phosphorus pentoxide (P_2O_5) ha^{-1}], (ii) compost with three levels (0, 15, and 30 t ha^{-1}) and (iii) limestone with two levels (0 and 8 t ha^{-1} calcium carbonate equivalent), based on 200,000 plants ha^{-1}.

The compost was made from forestry waste, woody materials, food waste unfit for consumption or processing (meat, fish, fruits, vegetables, dairy, and bakery), and from fruit and vegetable markets, properly source separated. Gafsa phosphate is a phosphate fertilizer certified for organic farming with the description of soft rock phosphate, with 26.5% of total P_2O_5, 15% of P_2O_5 soluble in 2% formic acid. Lime was used in powder consisting of 96% calcium carbonate ($CaCO_3$).

Batavia lettuce (cv. 'Jazzie') was sown in polystyrene trays with 220 cells, containing the substrate based on peat and sand. Subsequently the cells were covered with vermiculite. Transplanting occurred in September, 28 days after seeding, to pots (20 cm in diameter) with 8 kg of a sandy loam soil collected from 0 to 20 cm depth in a field left fallow for two years and used in previous 5 years according to OA regulations. Irrigation was performed so that the water content in the soil was not limiting for plant growth. The percolating water was restored to the soil and weeds were removed immediately after emergence. There were two pesticide treatments with a copper fungicide (certified for OA) for preventive action (Kocide DF Agroquisa; DuPont, Wilmington, DE, USA).

The harvest took place 56 days after transplantation. The substrate was removed from the pot and immersed in tap water to separate the soil from the roots. The shoot was separated from the roots and each part was weighted immediately for fresh weight. Dry weight was determined after drying shoots and roots in a thermoventilated oven at 65°C to constant weight.

Compost dry matter (DM) content, pH, electrical conductivity (EC) and organic matter content (OM) were determined by standard procedures (CEN, 1999). The DM was determined using a drying oven at a temperature of 75°C ± 5°C with not less than 50 g of the sample. The pH was measured with a pH meter in samples extracted with water at 22°C ± 3°C in an extraction ratio of 1+5 (v/v) and the specific EC was measured in the same extract with a conductivity meter. The OM content was calculated by the loss of mass on ignition at 450°C for 6 h using a muffle furnace. Total N and P in the soil, composts and crops were measured by molecular spectrophotometry after digestion with sulfuric acid, potassium (K) was measured by flame photometry, and calcium (Ca), magnesium (Mg), and Fe by atomic spectrophotometry, after nitric-perchloric acid digestion. Mineral N of fresh compost was extracted with 2 M potassium chloride (KCl) 1:5 from the frozen samples. Contents of NH_4^+-N and nitrate (NO_3^-)-N in the extracts were determined by an automated colorimetric procedure, based on the Berthelot's method and the Griess–Ilosvay's reaction respectively for

TABLE 1 Soil characteristics [mean ± standard deviation (SD)]

Soil	pH	EC dS m^{-1}	OM g kg^{-1}	C/N	NH_4^+-N	NO_3^--N	N	P	K
					......mg kg^{-1}......		..........g kg^{-1}..........		
Mean	5,8	0,1	30,3	15	14	26	1.2	1.6	12
SD	±0,1	±0,01	±6,9	±5,7	±11	±14	±0.7	±0.2	±0.4

Organic matter (OM) and nutrient contents are expressed on dry matter basis.

NH_4^+ and NO_3^-, (Houba et al., 1995). For the calculation of the carbon (C)/N ratio, C content in the soil was estimated by dividing the OM content by the van Bemmelen factor (1.724) and in compost by a factor of 1.8 (Jiménez and Garcia, 1992).

Soil and compost characteristics are shown in Tables 1 and 2, respectively. Statistical analysis was carried out using SPSS 17.0 for Windows (SPSS Inc., Chicago, IL, USA). Analysis of variance (ANOVA) was performed by the general linear model SPSS procedure, and a probability level of $\alpha = 0.05$ was applied to determine statistical significance.

RESULTS AND DISCUSSION

Fresh weight of lettuce shoots was enhanced ($P \leq 0.05$) with the application of all fertilizers: lime, phosphate and compost (Figure 1). Mean yield increases of 23% and 20% were found for lime and phosphate, respectively, but the clearest increase was associated with compost as it contributed to an average yield raise of 63% when applied at the rate of 15 t ha^{-1} and doubled lettuce yield for the highest application rate (30 t ha^{-1}) compared with control. There was one significant two-way interaction, between lime and phosphate, because lettuce yield was neither increased with lime when phosphate was applied nor with phosphate when lime was applied (Table 3). However, other two-way and the three-way interactions were not significant.

The experimental soil had an acidic reaction with a pH value (5.8) below the lower limit recommended for growing lettuce (6–6.8; Maynard and Hochmuth, 1997). This explained lettuce yield increases with lime application compared to similar treatments without lime, for the overall treatments (Figure 1). However, yield increases when phosphate was applied were not

TABLE 2 Compost characteristics [mean ± standard deviation (SD)]

Compost	DM %	pH	EC dS m^{-1}	OM g kg^{-1}	C/N	NH_4^+-N	NO_3^--N	N	P	K	Ca	Mg
						......mg kg^{-1}......		............g kg^{-1}............				
Mean	87	9.0	2.5	562	12	1157	687	25.8	5.8	10.9	3.6	10.6
SD	±0.8	±0.1	±0.17	±1.1	±0.2	±143	±194	±2.5	±0.6	±1.9	±0.7	±1.4

Organic matter (OM) and nutrient contents are expressed on dry matter basis.

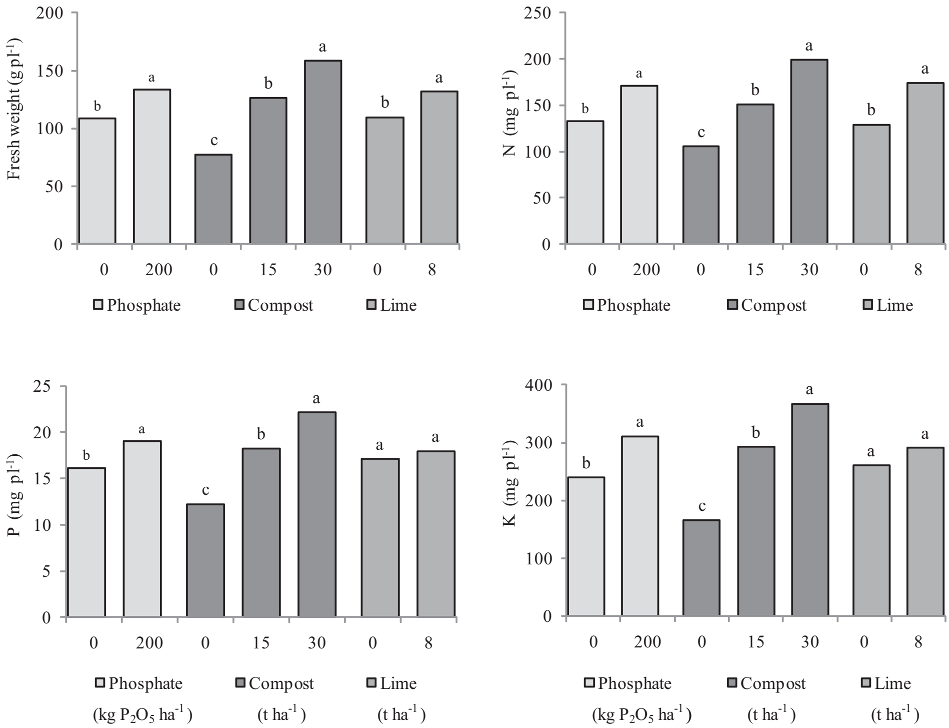

FIGURE 1 Fresh weight and N, P and K accumulation in organic lettuce shoots with phosphate, compost or lime application. Different letters above bars of the same fertilizer mean significant differences between means ($P \leq 0.05$).

TABLE 3 Fresh weight (FW), dry weight (DW) and nutrient contents in lettuce shoots

			Lettuce shoots							
Phosphate kg P_2O_5 ha^{-1}	Compost t ha^{-1}	Lime t ha^{-1}	FW	DW	N	P	K	Ca	Mg	Fe
			.... g pl^{-1}		.... mg g^{-1} DW					
0	0	0	57.8	3.4	21.3	2.7	32.9	6.6	3.2	1.7
0	0	8	88.7	4.9	26.5	2.9	36.0	10.8	4.2	1.6
0	15	0	94.5	5.3	20.8	3.1	44.9	11.6	2.9	2.4
0	15	8	138.1	6.6	25.0	2.8	47.1	12.2	3.4	1.3
0	30	0	99.1	5.0	20.0	3.4	34.9	6.5	2.6	0.8
0	30	8	172.0	7.7	28.4	2.9	52.5	10.5	3.4	1.6
200	0	0	86.1	4.9	23.5	2.7	41.9	6.8	4.6	1.3
200	0	8	77.3	4.4	28.5	2.9	41.4	9.3	5.2	1.2
200	15	0	134.1	7.4	21.4	2.8	47.5	7.2	3.6	1.1
200	15	8	139.2	6.6	25.8	2.7	42.3	8.6	4.6	1.7
200	30	0	187.4	9.4	23.0	2.9	49.8	6.9	4.6	1.6
200	30	8	175.5	8.6	30.9	2.7	48.0	8.0	5.0	1.3
Least significant difference ($p \leq 0.05$)			48.1	2.3	6.0	0.4	13.0	6.8	1.8	2.2

TABLE 4 Fresh weight (FW), dry weight (DW) and nutrient contents in lettuce roots

			Lettuce shoots							
Phosphate kg P_2O_5 ha^{-1}	Compost t ha^{-1}	Lime t ha^{-1}	FW .... g pl^{-1}	DW	N .... mg g^{-1} DW	P	K	Ca	Mg	Fe
0	0	0	4.8	0.5	10.6	1.7	6.6	1.1	1.0	0.4
0	0	8	5.4	0.6	13.6	1.8	6.6	1.8	1.0	0.4
0	15	0	6.7	0.8	10.1	1.6	8.5	1.7	1.1	0.4
0	15	8	8.6	0.9	10.3	1.4	7.1	2.2	1.2	0.6
0	30	0	6.7	0.8	8.9	2.0	8.4	1.4	0.8	0.4
0	30	8	9.5	1.0	11.9	1.6	11.0	1.7	1.0	0.8
200	0	0	5.5	0.6	11.0	1.5	8.1	2.2	1.5	0.6
200	0	8	4.7	0.5	13.8	1.7	5.7	4.1	2.2	0.4
200	15	0	7.4	0.9	9.9	1.6	6.3	0.8	0.5	0.2
200	15	8	7.7	0.8	13.7	1.7	9.3	4.4	1.3	0.4
200	30	0	11.3	1.3	9.9	1.6	10.2	1.1	0.7	0.5
200	30	8	9.1	1.0	13.0	1.5	10.3	1.4	1.0	0.5
Least significant difference ($p \leq 0.05$)			2.2	0.3	3.4	0.3	4.4	2.1	0.8	0.4

further improved with lime, suggesting that a limitation on the growth of lettuce in the soil without lime was the reduced solubility of P as a result of phosphate precipitation (Holford, 1997; Devau et al., 2009). Apparently, P fertilization could replace the need for liming and liming could replace the need for P fertilization. When lime was applied together with phosphate, the soluble P could react with Ca to form insoluble phosphates that precipitate, contributing in some measure to decrease P availability (Iyamuremye et al. 1996). Therefore, especially in organic agriculture, liming the soil to the proper pH for the crops to be grown, and selecting appropriate crops for the soils available is critical to using inputs efficiently.

Lettuce shoot dry weight (DW) increased ($P \leq 0.05$) with the application of compost and also with Gafsa phosphate (Table 3). The accumulation of N, P, and K increased in lettuce shoots ($P \leq 0.05$) produced with phosphate or compost but only the accumulation of N was improved with lime application (Figure 1). A significant two-way interaction was found between lime and phosphate because N, P, and K uptake neither increased with lime when phosphate was supplied nor with phosphate when lime was applied. Other two-way and three-way interactions were not significant.

The average increase in N accumulation of lettuce with 15 t ha^{-1} and 30 t ha^{-1} of compost compared to 0 t ha^{-1} was respectively 48 and 99 mg N plant^{-1}. This increase in N uptake was less than the amount of mineral N (NH_4^+-N and NO_3^--N) available in compost at the rates of 15 t ha^{-1} and 30 t ha^{-1} (respectively to 120 and 240 mg mineral N plant^{-1}). This suggests that lettuce growth with compost was not limited by N availability. Since mineral N contained in compost was above the difference between the accumulations of N in treated and control lettuces, it was not possible to estimate the

TABLE 5 Ratios between shoot and roots nutrient contents in organic lettuce

			Shoot: root nutrient content					
Phosphate kg P_2O_5 ha^{-1}	Compost t ha^{-1}	Lime t ha^{-1}	N	P	K	Ca	Mg	Fe
			mg g^{-1} DW					
0	0	0	2.0	1.6	5.0	6.0	3.2	4.3
0	0	8	1.9	1.6	5.5	6.0	4.2	4.0
0	15	0	2.1	1.9	5.3	6.8	2.6	6.0
0	15	8	2.4	2.0	6.6	5.5	2.8	2.2
0	30	0	2.2	1.7	4.2	4.6	3.3	2.0
0	30	8	2.4	1.8	4.8	6.2	3.4	2.0
200	0	0	2.1	1.8	5.2	3.1	3.1	2.2
200	0	8	2.1	1.7	7.3	2.3	2.4	3.0
200	15	0	2.2	1.8	7.5	9.0	7.2	5.5
200	15	8	1.9	1.6	4.5	2.0	3.5	4.3
200	30	0	2.3	1.8	4.9	6.3	6.6	3.2
200	30	8	2.4	1.8	4.7	5.7	5.0	2.6
Least significant difference ($p \leq 0.05$)			0.4	0.3	2.7	4.3	3.1	2.1

mineralization of organic N during the experimental period based on N uptake differences. This also shows that the use efficiency of mineral N of the compost at the rate of 30 t ha^{-1} was less than 100%, revealing risks of N losses by leaching.

The compost content of NH_4^+-N (1157 mg kg^{-1} DM) was above the content limit of 400 mg kg^{-1} DM suggested as an indicator of stabilization of composts (Zucconi and De Bertoldi, 1987). Compost maturity can also be defined in terms of nitrification (Bernal et al., 2009). An NH_4^+–N/ NO_3^-–N ratio less than 0.16 was suggested by Bernal et al. (1998) as a maturity index for compost, irrespective of the origin. The Compost Maturity Index recommended by CCQC (2001) states that a ratio less than 0.5 indicate that composts are well mature and Larney and Hao (2007) proposed that values <1 denote very stable or mature material. Here, this ratio was 1.7 indicating that compost was not properly matured. However, the growth of lettuce was not inhibited with increasing rates of compost, suggesting that there has been no toxic effect with the application of this compost, which in addition to nutrient availability, may have contributed to the improvement of the physical and biological soil properties. In contrast to stabilized composts that generally provide fewer nutrients compared to fresh materials, this compost had a high mineral N content, a low C/N ratio, and appears to be a good fertilizer for fast-growing vegetables such as lettuce. Nevertheless, a longer period of compost maturation is recommended to produce stabilized compost suitable for unrestricted vegetable crop use.

The highest lettuce nutrient contents were found for K and N. The N content did not change with the application of phosphate or compost but increased with lime application (Table 3). Magnesium content increased with phosphate whereas other differences in nutrient contents between lettuces were not significant. Therefore, nutrient uptake depended mostly on the accumulation of dry weight rather than on differences in nutrient contents.

Phosphorus is an essential nutrient that is often added to soil to increase crop production (Sims et al., 2000), particularly in acid soils where P availability decreases. When the level of available P is low, microbial biomass and the roots may increase the production of phosphatases responsible for the mineralization of P (Chabot et al., 1996). On the other hand, perhaps more than on the soil P availability, P uptake depends on plant demand, in particular caused by N uptake for the synthesis of proteins. This may explain why only small changes were found in the ratio N/P in the plant, even for large variations in soil characteristics, as demonstrated in this study where the ratio N/P varied only between 7–8 in the roots and 8–10 in the shoots, and did not change with the application of either phosphate or compost. The ratio between N content and other nutrient contents in lettuce shoots shows values of 2–3 for the N/Ca ratio and 6–7 for the N/Mg ratio. Only the ratio N/K was less than 1 in the leaves but not in the roots (Table 4) that showed K contents (7–10 mg g^{-1}) far below those found for the leaves (38–46 mg g^{-1}; Table 3).

Nutrient contents in leaves were always higher than nutrient contents in roots (Table 5). The N and P contents in the leaves doubled those of the roots, the K and Ca were approximately five times higher in leaves and the levels of Mg and Fe increased from three to four times. The ratio N/P was higher in leaves compared to roots, but the ratio between N content and the content of any of the other nutrients was higher in roots. These facts show that the distribution of nutrients between leaves and roots is held for the benefit of the leaves, but to a lesser extent for P compared to other nutrients.

CONCLUSIONS

The increasing rates (between 0 and 30 t ha^{-1}) of source separated organic municipal waste compost substantially increased organic lettuce yield because of compost high mineral N content. However, the use efficiency of mineral N of the compost was less than 100%, revealing risks of N losses by leaching.

Although the application of lime and phosphate have increased lettuce yield, this was not observed for each fertilizer regardless of the rate of the other fertilizer. The Gafsa phosphate at 200 kg ha^{-1} increased lettuce yield only when the limestone was not applied, whereas liming increased yield only when the phosphate was not applied, showing that the lime allowed better uptake of available P, in this case eliminating the need for applied P, and that liming can often improve fertilizer use efficiency, reducing needed application rates. The compost used here can be recommended for fast growing vegetables such as organic lettuce and the recommendation for P application has to be estimated based on soil P availability and crop productivity but also on soil acidity and liming recommendation.

REFERENCES

Ambus, P., L. K. Kure, and E. S. Jensen. 2002. Gross N transformation after application of household compost and domestic sewage sludge on agricultural soils. *Agronomie* 22: 723–730.

Bernal, M. P., J. A. Alburquerque, and R. Moral. 2009. Composting of animal manures and chemical criteria for compost maturity assessment. A review. *Bioresource Technology* 100: 5444–5453.

Bernal, M. P., C. Paredes, M. A. Sánchez–Monedero, and J. Cegarra. 1998. Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Bioresource Technology* 63: 91–99.

Brito, L. M. 2001. Lettuce (*Lactuca sativa* L.) and cabbage (*Brassica oleracea* var. *Capitata*) growth in soil mixed with municipal solid waste compost and paper mill sludge composted with bark. *Acta Horticulturae* 563: 131–137.

CCQC. 2001. *California compost quality council. compost maturity index. Technical Report.* Nevada City, CA: California Compost Quality Council.

Carpenter-Boggs, L., A. C. Kennedy, and J. P. Reganold. 2000. Organic and biodynamic management: Effects on soil biology. *Soil Science Society of America* 54: 1651–1659.

CEN. 1999. *European Standards - Soil Improvers and Growing Media.* Brussels: European Committee for Standardization.

Chabot, J., H. Antoun, and M. P. Cescas. 1996. Growth promotion of maize and lettuce by phosphate-solubilising *Rhizobum leguminosarum* biovar. phaseoli. *Plant and Soil*: 184: 311–321.

Corrêa, R. M., C. W. A. Nascimento, S. K. Sosza, F. J. Freire, and G. B. Silva. 2005. Gafsa rock phosphate and triple superphosphate for dry matter production and P uptake by corn. *Science Agriculture* 62: 159–164.

Devau, N., E. Cadre, P. Hinsinger, B. Jaillard, and F. Gérard. 2009. Soil pH controls the environmental availability of phosphorus: experimental and mechanistic modelling approaches. *Journal Applied Geochemistry* 24: 2163–2174.

Eghball, B. 2002. Soil properties as influenced by phosphorus- and nitrogen-based manure and compost applications. *Agronomy Journal* 94: 128–135.

Flavel, T. C., and D. V. Murphy. 2006. Carbon and nitrogen mineralization rates after application of organic amendments to soil. *Journal of Environmental Quality* 35: 183–193.

Gabrielle, B., J. De-Silveira, S. Houot, and C. Francou. 2004. Simulating urban waste compost effects on carbon and nitrogen dynamics using a biochemical index. *Journal of Environmental Quality* 33: 2333–2342.

Holford, I. C. R. 1997. Soil phosphorus: its measurement, and its uptake by plants. *Australian Journal of Soil Research* 35: 227–239.

Houba, V. J. G., J. J. Van der Lee, and I. Novozamsky. 1995. *Soil Analysis Procedures – Other Procedures, Part 5B.* Wageningen, the Netherlands: Department of Soil Science and Plant Nutrition, Wageningen Agricultural University.

Iyamuremye, F., R. P. Dick, and J. Baham. 1996. Organic amendments and phosphorus dynamics: I phosphorus chemistry and sorption. *Soil Science* 161: 426–435.

Jiao, Y., W. H. Hendershot, and J. K. Whalen. 2008. Modeling phosphate adsorption by agricultural and natural soils. *Soil Science Society of America Journal* 72: 1078–1084.

Jiménez, E. I., and V. P. Garcia. 1992. Relationship between organic carbon and total organic matter in municipal solid waste and city refuse compost. *Bioresource Technology* 41: 256–272.

Johnston, E., P. R. Poulton, and K. Coleman. 2009. Soil Organic Matter: Its importance in sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy* 101: 1–57.

Larney, F. J., and X. Hao. 2007. A review of composting as a management alternative for beef cattle feedlot manure in southern Alberta, Canada. *Bioresource Technology* 98: 3221–3227.

Lear, G., M. J. Harbottle, C. J. van der Gast, S. A. Jackman, C. J. Knowles, G. Sills, and I. P. Thompson. 2004. The effect of electrokinetics on soil microbial communities. *Soil Biology and Biochemistry* 11: 1751–1760.

Maynard, D. N. and J. G. Hochmuth. 1997. *Knott's Handbook for Vegetable Growers*. New York: John Wiley and Sons.

Montemurro, F. 2010. Are organic fertilizing strategies able to improve lettuce yield, use of nitrogen and N status. *Journal of Plant Nutrition* 33: 1980–1997.

Sample, E. C., R. J. Soper, and G. J. Racz. 1980. Reactions of phosphate fertilizers in soils. In: *The Role of Phosphorus in Agriculture*, ed. F. E. Khasawneh, pp. 263–304. Madison, WI: American Society of Agronomy.

Sikora, L. J., and R. A. K. Szmidt. 2001. Nitrogen sources, mineralization rates, and nitrogen nutrition benefits to plants from composts. In: *Compost Utilization in Horticultural Cropping Systems*, eds. P. J. Stoffella, and B. A. Kahn, pp. 287–305. New York: Lewis Publishers.

Sims, J. T., A. C. Edwards, O. F. Schoumans, and R. R. Simard. 2000. Integrating soil phosphorus testing into environmentally based agricultural management practices. *Journal of Environmental Quality* 29: 60–71.

Wong, J. W. C., K. K. Ma, K. M. Fang, and C. Cheung. 1999. Utilization of a manure compost for organic farming in Hong Kong. *Bioresource Technology* 67: 43–46.

Yun, S., and H. Ro. 2009. Natural 15N abundance of plant and soil inorganic-N as evidence for over-fertilization with compost. *Soil Biology and Biochemistry* 41: 1541–1547.

Zucconi, F., and M. de Bertoldi. 1987. Composts specifications for the production and characterization of composts from municipal solid waste. In: *Compost: Quality and Use*, eds. M. de Bertoldi, M. P Ferranti, P. L'Hermite, and F. Zucconi, pp. 30–50. London: Elsevier Applied Science.