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Review

A review of the use of composted municipal solid waste in agriculture

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Abstract

Municipal solid waste (MSW) compost is increasingly used in agriculture as a soil conditioner but also as a fertilizer. Proponents of this practice consider it an important recycling tool since MSW would otherwise be landfilled and critics are concerned with its often elevated metal concentrations. Large amounts of MSW compost are frequently used in agriculture to meet crop N requirements and for the addition of organic matter. The main concern is loading the soil with metals that can result in increased metal content of crops. Furthermore, in some cases, metals and excess nutrients can move through the soil profile into groundwater. Municipal solid waste compost has also been reported to have high salt concentrations, which can inhibit plant growth and negatively affect soil structure. A review of relevant agricultural studies is presented as well as recommendations for improving MSW compost quality. Its safe use in agriculture can be ensured with source separation (or triage of MSW to be composted) as well as the development and implementation of comprehensive industry standards.

Keywords: Compost; Metal contamination; Municipal solid waste; Organic waste recycling

Contents

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1. Introduction

Municipal solid waste (MSW) is largely made-up of kitchen and yard waste, and its composting has been adopted by many municipalities (Otten, 2001). Composting MSW is seen as a method of diverting organic waste materials from landfills while creating a product, at relatively low-cost, that is suitable for agricultural purposes (Eriksen et al., 1999; Wolkowski, 2003). This trend may be attributed to economic and environmental factors, such as municipal landfill capacity; costs associated with landfilling and transportation of materials; adoption of legislation to protect the environment; decreasing the use of commercial fertilizers; increasing the capacity for household waste recycling and improved quality of compost products (He et al., 1992; Otten, 2001; Hansen et al., 2006; Zhang et al., 2006). In Canada, MSW composting facilities in Guelph, Ontario, and Lunenburg, Nova Scotia have shown landfill diversion rates in excess of 70 and 67%, respectively (Otten, 2001). Composting MSW reduces the volume of the waste, kills pathogens that may be present, decreases germination of weeds in agricultural fields, and destroys malodorous compounds (Jakobsen, 1995). With rising interest in organic agriculture, the production of organic-grade MSW compost for agriculture is also gaining popularity because of its positive effect on biological, physical, and chemical soil properties (Iglesias-Jimenez and Alvarez, 1993).

The quality of MSW compost is dependent on many sources of variation including the composting facility design, feedstock source and proportions used, composting procedure, and length of maturation. In addition to the differences between MSW composts, when it is applied to different types of field soils, there are further variabilities in plant response. A review of field studies using MSW compost is presented below and recommendations are offered for the safe production and use of MSW compost in agriculture. Table 1 provides a summary of the literature cited, the source of the MSW compost, the soil types it was applied to, the crops tested, and the application rates.

2. Physical soil properties

A primary benefit of MSW compost is the high organic matter content and low bulk density (He et al., 1995; Soumare et al., 2003). A survey of MSW compost reported that on average, 20% of the total C in MSW compost was organic C, 8% carbonate C, and 71% residual C which may have included organic C components (He et al., 1995). Furthermore, the majority of the humic substances found in MSW compost were identified as humic acid, with a humic acid to fulvic acid ratio of 3.55 (He et al., 1995). Humic acid is generally considered to be more stable than fulvic acid and has been associated with increasing the buffering capacity of soil (He et al., 1995; Garcia-Gil et al., 2004). When MSW compost was applied to soil at application rates of 20 and 80 Mg ha^{-1}, the major structural units of humic acid in MSW compost were incorporated into the humic acids in the soil (Garcia-Gil et al., 2004). The change in soil structure persisted and was structurally changed 9 years after the initial application (Garcia-Gil et al., 2004). Repeated application of MSW compost consistently increased soil organic matter content and soil C/N ratio to levels greater than those of unamended soil (Perucci, 1990; Crecchio et al., 2004; Garcia-Gil et al., 2004; Montemurro et al., 2006; Walter et al., 2006). Municipal solid waste compost had a high water holding capacity because of its organic matter content, which in turn improved the water holding capacity of the soil (Hernando et al., 1989; Soumare et al., 2003). Furthermore, application rates of 30 and 60 Mg ha^{-1} of MSW compost increased the aggregate stability of soil through the formation of cationic bridges thereby, improving the soil structure (Hernando et al., 1989). Another study also found that the addition of mature MSW compost, in this case to a silt loam, increased aggregate stability (Annabi et al., 2007).

The environmental fate of some pesticides in soil has been found to be affected by the application of MSW compost to soil because of the addition of organic matter. It was reported that the addition of 90 Mg ha^{-1} of MSW compost to soil increased the absorption of triasulfuron significantly (Said-Pullicino et al., 2004). The increase in organic matter was thought to also increase the sorption sites available for adsorption. It was also observed that triasulfuron is selectively adsorbed by particulate organic matter fractions in compost (Said-Pullicino et al., 2004). The adsorption of the pesticide to the organic matter, however, tended to protect the pesticide from microbial activity resulting in increased degradation time (Said-Pullicino et al., 2004). This study suggested that compost, through the addition of hydrophobic dissolved organic matter to soil, can hinder the breakdown of some chemicals in soil thus increasing their persistence in soils.

Table 1
Summary of agricultural studies of MSW compost discussed in this review

MSW source	Soil type/pH/E.C. (dS/m)	Crop	Rate (Mg ha^{-1})	Comments	Reference
Source-separated from Netanya sewage treatment plant, Israel	Sand/7.5/8.5	Wheat	0.03, 0.06, 0.12	Increase yield, downward movement of P observed, pot experiment	Bar-Tal et al. (2004)
Calcutta city wastes, India	Clay/5.5/2.7–2.8	Rice	5.9–6; 40	Increased yield, pH (field experiment); high rates did not affect microbiology of soil (pot experiment)	Bhattacharyya et al. (2003a,b)
Castel di Sangro, Italy	Clay/8.3	N/A	12–24	Increased enzyme activities but no effect of community structure 6 years after application	Crecchio et al. (2001, 2004)
Not stated	Sand/6.4	Maize	0, 63, 126, 189 (fw)	First year N immobilization	Eriksen et al. (1999)
Valdemingomez MSW treatment plant, Madrid, Spain	Sandy loam/6.4/7.0 (2001)	Barley	20 and 80	Increased microbial metabolism in soil; long-term increased buffering capacity of soil	Garcia-Gil et al. (2000, 2004)
Gesenu MSW treatment plant, Perugia, Italy	Sandy loam/7.7; clay silt loam/7.8	N/A	~50	Increased soil Zn concentrations in both soils, pot experiment	Giusquiani et al. (1988)
Gesenu MSW treatment plant, Perugia, Italy	Clay loam/8.3	Corn	30, 90, and 270	Increased enzyme activities despite adding three times the heavy metals limit specified by Italian law	Giusquiani et al. (1994)
Valdemingomez urban solid waste treatment plant, Madrid, Spain	Sandy clay loam/6.1/10	N/A	15, 30, and 60	Increased water holding capacity, pH, soil Zn and Cu concentrations, pot experiment	Hernando et al. (1989)
Santa Cruz de Tenerife, Canary Islands, Spain	Clay loam/5.8/16	Ryegrass	10, 20, 30, 40, and 50	High rates can provide sufficient N for ryegrass, E.C. increased with rate, soil P retention decreased, pot experiment	Iglesias-Jimenez and Alvarez (1993) and Iglesias-Jimenez et al. (1993)
Not stated	Clay loam/7.7/0.8	Spinach	0, ~20, 40, 60, and 80	Increased yield, increased P, Mn, Pb, Na, and Cl uptake, pot experiment	Maftoun et al. (2004)
Truman, MN (OTVD French technology) and Buffalo, MN (Buhler Swiss technology)	Sandy loam/5.8	Corn	90 and 270	Composts highly variable year to year	Mamo et al. (1999)
Source-separated Lunenburg regional recycling and composting facility, NS, Canada	Sandy loam/potatoes: 5.8, sweet corn: 6.5	Potatoes and sweet corn	Potatoes: 21.7, 43.4, and 65.1; sweet corn: 7.5, 15, and 22.5 (half these amounts were applied the second year)	pH increased, compost supplied similar amount of P as mineral fertilizer	Mkhabela and Warman (2005)
Cupello engineering, Italy	Clay/7.4	Alfalfa and cocksfoot	Alfalfa: ~150, cocksfoot: ~60	Organic carbon increased	Montemurro et al. (2006)
Sevilla city wastes (fraction <30mm), Spain	Sandy clay loam/7.8	Clover	100 (2 applications)	Increased N, Zn, Cu, Ni, and Cr uptake, pot experiment	Murillo and Cabrera (1997)
Lunenberg regional recycling and composting facility, NS, Canada	Sandy loam/4.55; gravelly loams/4.53, 4.80	Blueberries	~35, 70, and 140 (2 applications)	Increased soil Mn at high rate, increased leaf Ni at high rate	Murphy and Warman (2001)
Agrisoil compost	Very gravelly loam/7.2–7.6	Tomatoes; squash	24 and 48	Increased soil concentrations of Cd, Cu, Pb, Ni, and Zn, fruit uptake was not observed	Ozores-Hampton and Hanlon (1997)

Table 1 (*Continued*)

MSW source	Soil type/pH/E.C. (dS/m)	Crop	Rate (Mg ha^{-1})	Comments	Reference
Murcia, Spain	Silty clay loam/7.8/1.8	N/A	65 and 260	Increased natural plant diversity, microbial biomass C, and soil basal respiration; changes long-term (8 years)	Pascual et al. (1999)
Not stated	Clay loam/8.5	N/A	75	Biomass C, N, S, and P increased, all enzyme activities increased, pot experiment	Perucci (1990)
Schio (Vicenza), unseparated waste, Italy	Medium sandy texture/7.7	Merlot vineyard grapes	54	Use of MSW compost over 6 years increased concentration of Ni, Pb, Cd, and Cr, in soils, grapevine leaves, and musts	Pinamonti et al. (1999)
Municipality of Lunenberg central MSW composting facility, source-separated, NS, Canada	Sandy loam/6.1	Barley and wheat	~0, 75, 150, and 225	MSW compost did not increase plant uptake of metals	Rodd et al. (2002)
MSW composting plant, Setubal, Portugal	Sandy loam/7.9; sand/8.2; sand/6.2	Potatoes	15	Yield improved only in sands; small increase in soil Pb, Cu, and Zn concentrations in sand/8.2	Sebastiao et al. (2000)
Lunenberg Municipal solid waste compost, NS, Canada	Sandy loam/~6.0	Strawberries	~37.5 (first year; half that amount second year)	MSW compost increased yield of Sparkle variety, increased soil Na and Ca	Shanmugam and Warman (2004)
Madrid, Spain	Sandy loam/8.3/9.5	Shrubs	0, 40, 80, and 120	Increased EC, organic carbon, total soil N at highest rate, soil Zn, Pb, and Cu, and increased plant uptake of Zn	Walter et al. (2006)
Lunenberg regional recycling and composting facility, NS, Canada	Sandy loam/7.93	Corn, potatoes, squash	Corn: 6.2, 12.4, 18.6; potatoes: 8.9, 17.8, 26.7; squash: 5, 10, 15	Increase plant Cu concentrations, increased pH	Warman and Rodd (1998)
Columbia County recycling and composting facility, Wisconsin, USA	Silt loam/5.4	Corn	22.5, 45, and 90 (dw)	Highest rate increased yield equal to fertilizer treatment; soil nitrate lower where MSW compost was applied	Wolkowski (2003)
Lunenberg regional recycling and composting facility, NS, Canada	Sandy loam/4.55; gravelly loams/4.53, 4.80	Blueberries	~35, 70, and 140 (2 applications)	Increased soil K	Warman et al. (2004)
Edmonton, Ab, Canada	Site 1: silt clay loam/5.8; site 2: silt loam/6.8	Barley, wheat, canola	50, 100, and 200 (4 applications)	Compost releases N in first 2 years, compost increased pH and EC, Soil Zn concentrations increased with increasing rates	Zhang et al. (2006)
Lunenburg regional recycling and composting facility, NS, Canada	Sandy loam/Basil: 5.33; Swiss chard: 5.99	Basil and Swiss chard	~200, 400, and 600	Compost increased soil concentrations of Cu and Zn but plant uptake was not observed; pot experiment	Zheljazkov and Warman (2004a,b)
Colchester regional composting facility, Kemptown, NS, Canada	Coarse loam/6.6	Timothy and red clover	~45 and 90	Compost increased yield, tissue S, soil and tissue Na concentrations (high rate)	Zheljazkov et al. (2006)

3. Biological soil properties

Soil ecology is increasingly being used to evaluate soil quality. It is thought that soil microbiological properties are most sensitive to changes in the soil environment (Pankhurst et al., 1997; Crecchio et al., 2001). Biomass N, C, and S showed increases in the soil immediately after compost addition and for up to 1 month, while biomass P showed an increasing trend for 5 months (Perucci, 1990). Application of 2.5, 10, 20, and 40 Mg ha^{-1} MSW compost increased soil microbial biomass C and soil respiration (an index of general metabolic activity of soil microorganisms) when compared to a control (Bhattacharyya et al., 2003a). In a long-term experiment, it was found that multiple additions of MSW compost at rates of 20 and 80 Mg ha^{-1} increased microbial biomass C, and this increase persisted 8 years after application (Garcia-Gil et al., 2000). Soil basal respiration rate, a parameter used to monitor microbial activity, was also seen to increase where MSW compost was applied when compared to a control for 8 years after application (Pascual et al., 1999). A field experiment measuring inositol phosphates found that application of 6–18 Mg ha^{-1} had a negative effect on total inositol phosphate soil concentrations (Warman and Munroe, 2000). The principal form of organic P in soils is inositol phosphates which are thought to be of microbial origin (Stevenson, 1986).

Another measure of soil microbial health is the activity of soil enzymes involved in the transformation of the principal nutrients (Crecchio et al., 2004). After application of 75 Mg ha^{-1} of MSW compost, the enzyme activities of phosphodiesterase, alkaline phosphomonoesterase, arylsulphatase, deaminase, urease, and protease were increased (Perucci, 1990). Increases in these enzyme activities above baseline levels persisted for 3 months after application (Perucci, 1990). The activity of phosphatase remained constant in the soil after reaching its maximum value, and so it may be concluded that MSW compost may stimulate the transformation of organic P to its inorganic and available form (Perucci, 1990). Enzyme activities of arylsulphatase, dehydrogenase, and L-asparaginase have also been seen to increase with the addition of MSW compost, with application rates up to 90 Mg ha^{-1}, while the activities of phosphodiesterase and phosphomonoesterase increased linearly with increasing application rates (Giusquiani et al., 1994). These increases occurred despite the addition of heavy metals at three times the limit set by Italian law. Dehydrogenase activity was affected in the long-term when MSW compost was applied at low rates (Pascual et al., 1999). Increases of urease and acid phosphatase activities were observed in soils treated with 2.5–40 Mg ha^{-1} and were proportional to MSW compost application rate (Bhattacharyya et al., 2003a). The enzyme activities of β-glucosidase and nitrate reductase have also been reported to increase with the addition of MSW compost when compared to a control (Crecchio et al., 2001). Some enzyme activities were reported to decrease where MSW compost was applied. For example, protease activities were found to decrease where only 24 Mg ha^{-1} MSW compost was applied, probably reflecting the low protein content of the product (Crecchio et al., 2004). Furthermore, it was found that the addition of MSW compost at 20 and 80 Mg ha^{-1} inhibited the activity of urease and protease (Garcia-Gil et al., 2000). The decrease, in both cases, was attributed to the potential toxic effects exerted by trace elements in this particular compost (Garcia-Gil et al., 2000; Crecchio et al., 2004). The composts used in the latter studies had much higher concentrations of Cu and Zn than other studies cited above and may explain the discrepancy in results. Some authors suggest that the effect of metals on soil enzyme activities seems to be dependent on the time of application, their concentration, and soil characteristics (Crecchio et al., 2001). Sandaa et al. (1999) found a pronounced reduction of bacterial diversity as well as changes in bacterial community structure in the presence of low metal concentrations, below the European upper legal limits, when compared to a control. Variability of metal levels in MSW compost somewhat hinders the ability to directly compare studies because of the sensitivity of soil microorganism to heavy metal stress (Smit et al., 1997; Giller et al., 1998). Studies on the effects of MSW compost on soil biology should include metal analysis results for this reason. While MSW compost seems to greatly affect soil enzyme activities, no short term change in the structure of the bacterial community, measured using molecular techniques, have been observed (Crecchio et al., 2001, 2004).

The thermophilic stage of composting occurs as microorganisms multiply in the pile and is characterized by increased temperatures ranging from 45 to 70 °C (Poincelot, 1975). The thermophilic stage is also important in decreasing the populations of pathogens in MSW compost, which cannot live at these high temperatures. Total faecal coliforms, and specifically *Escherichia coli*, faecal *Streptococci*, *Staphylococci*, *Salmonella*, and *Shigella* decreased greatly in numbers in MSW compost after the compost reached temperatures above 55 °C (Hassen et al., 2001). However, regrowth of fecal coliforms was observed in all windrows tested and may have posed a health risk when the piles were turned.

4. Chemical properties

4.1. pH effects

Increased soil pH is regarded as a major advantage when MSW compost is used (Mkhabela and Warman, 2005). Increases in soil pH from 6.1 to 7.6 (Hernando et al., 1989), 5.8 to 6.4 (Maynard, 1995), 5.9 to 6.3, and 5.4 to 5.8 (Mkhabela and Warman, 2005), 5.3 to 6.6, and 6.0 to 6.6 (Zheljazkov and Warman, 2004a), 4.9 to 5.8 and 5.1 to 5.9 (Shanmugam, 2005), and 5.8 to 6.7 and 6.1 to 6.5 (Zhang et al., 2006) have been reported. These increases were usually proportional to the application rate. The increase in the pH of soil may be due to the mineralization of carbon and the subsequent production of OH^- ions by ligand exchange as well as the introduction of basic cations, such as K^+, Ca^{2+}, and Mg^{2+} (Mkhabela and Warman, 2005). It was found that blueberry (*Vaccinium angustifolium*, L.) leaves had lower Mn content in MSW compost-treated soils when compared to control and fertilizer treatments (Warman et al., 2004). The authors attributed the lower tissue Mn content to increased soil pH from MSW compost treatments since Mn availability decreased with increased soil pH (Warman et al., 2004). Immature MSW compost tended to have a lower pH prior to thermophilic stage due to the intensive production of organic acids (Leita and DeNobili, 1991). The lower pH, in this case, caused some metals in the compost to have higher water-extractable concentrations. Micronutrient and metal cations are most soluble and available for plant uptake under acidic conditions (Brady and Weil, 1996). Therefore, it may be possible to mitigate the heavy metal availability by managing the compost pH; however, some studies (reviewed below) have shown that this may not be so simple.

4.2. Electrical conductivity and salt effects

Plants are negatively affected by excess salts in soils and Na can be detrimental to soil structure. Electrical conductivity (EC) of the soil solution is related to the dissolved solutes content of soil and is often used as a measurement of soil salt content (Brady and Weil, 1996). A survey of selected United States MSW composts found that the EC of the composts were much higher than that of agricultural soils and their use in agriculture could potentially inhibit seed germination (He et al., 1995). Agricultural soils EC levels range from 0 to 4 dS m^{-1} while MSW composts ranged from 3.69 to 7.49 dS m^{-1} (Brady and Weil, 1996). Municipal solid waste composts applied at rates ranging from 40 to 120 Mg ha^{-1} were seen to proportionally increase the EC of soils to which they were applied (Iglesias-Jimenez and Alvarez, 1993; Walter et al., 2006). Increased soil EC values were found to decline over time, perhaps because of nutrient removal by crops and leaching (Zhang et al., 2006). Plant growth was not inhibited in these experiments; however, the authors suspected a decrease of soil biological activity due to the increased EC levels, which were higher than the threshold value for optimal soil biological activity (Iglesias-Jimenez and Alvarez, 1993).

Sodium concentrations in MSW composts range from 3.50 to 21.0 g Na kg^{-1} (He et al., 1995; Warman and Rodd, 1998; Garcia-Gil et al., 2000; Warman, 2001; Warman et al., 2004). Examination of strawberry (*Fragaria X ananassa*, L.) plots treated with different organic amendments and mineral fertilizers found that MSW compost resulted in significantly higher concentrations of soil Na in both years of the study (Shanmugam and Warman, 2004). Furthermore, MSW applied to provide 95 and 195 N kg ha^{-1} (approximately 45 and 90 Mg ha^{-1}, respectively) increased Na concentrations and the high compost treatment raised timothy (*Phleum pratense*, L.) and red clover (*Trifolium pratense*, L.) forage tissue Na when compared to control and mineral fertilizer treatments in fields that hold water late in the spring (Zheljazkov et al., 2006). Increased uptake of Na and Cl by spinach (*Spinacia oleracea*, L.) tops grown in soils treated with MSW compost was also observed where uptake increased with application rates (Maftoun et al., 2004).

Most studies concluded that MSW compost increased the EC value in soils. In some cases, soil EC levels were excessive and inhibited plant growth. Municipal solid waste compost has also been reported to increase plant Na and Cl content, which may be of concern to people on low-sodium diets. As with many other properties of MSW compost, the EC content of the MSW compost is likely related to the feedstock used in the compost and compost facility procedures (Hicklenton et al., 2001).

4.3. Nitrogen

The range of nitrogen concentrations that have been reported to be present in MSW compost is shown in Fig. 1. Nitrogen content in MSW compost is not regulated by the Canadian Council of Ministers of the Environment (CCME) or the United States Environmental Protection Agency (EPA) (CCME, 2005; U.S.EPA, 2000). The availability of nitrogen in MSW compost has been estimated at 10% in the first year after application with some reports of N release in the second year after application (deHaan, 1981; Eriksen

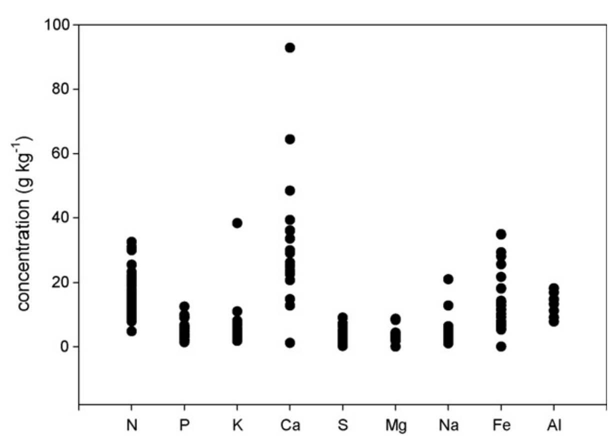

Fig. 1. Total concentrations of the macronutrients and metals present in MSW compost. Where for N, $n = 50$; P, $n = 30$; K, $n = 30$; Ca, $n = 21$; S, $n = 13$; Mg, $n = 21$; Na, $n = 18$; Fe, $n = 27$; Al, $n = 8$ (data taken from Giusquiani et al., 1988, 1994; Hernando et al., 1989; Perucci, 1990; Iglesias-Jimenez and Alvarez, 1993; He et al., 1995; Tisdell and Breslin, 1995; Ozores-Hampton and Hanlon, 1997; Warman and Rodd, 1998; Mamo et al., 1999; Pascual et al., 1999; Pinamonti et al., 1999; Sebastiao et al., 2000; Garcia-Gil et al., 2000; Crecchio et al., 2001; Hassen et al., 2001; Hicklenton et al., 2001; Murphy and Warman, 2001; Warman, 2001; Rodd et al., 2002; Bhattacharyya et al., 2003b; Wolkowski, 2003; Garcia-Gil et al., 2004; Maftoun et al., 2004; Warman et al., 2004; Zheljazkov and Warman, 2004a,b; Brunori et al., 2005; Mkhabela and Warman, 2005; Montemurro et al., 2006; Walter et al., 2006; Zheljazkov et al., 2006).

et al., 1999; Zhang et al., 2006). Iglesias-Jimenez and Alvarez (1993), however, reported 16–21% of the total N in MSW compost was available as NH_4NO_3 6 months after application and Hadas and Portnoy (1997) observed 22% recovery of total N, independent of soil type. While some studies showed that MSW compost increased soil N content, MSW compost is often reported to be less effective in supplying available N in the first year of application to the soil–plant system than inorganic mineral fertilizers (Iglesias-Jimenez and Alvarez, 1993; Warman and Rodd, 1998; Eriksen et al., 1999). The yield of potatoes (*Solanum tuberosum*, L.), sweet corn (*Zea mays*, L.), squash (*Cucurbita maxima*, L.), blueberries, strawberries (*F. X ananassa*, L.), ryegrass (*Lolium perenne*, L.), and boot-stage barley (*Hordeum vulgare*, L.) were lower in MSW compost-treated soils when compared with fertilizer-treated soils (Iglesias-Jimenez and Alvarez, 1993; Warman and Rodd, 1998; Rodd et al., 2002; Mkhabela and Warman, 2005; Shanmugam and Warman, 2004). Some research suggests, however, that high input of inorganic N can be obtained with rates of 40–50 Mg ha^{-1} MSW compost (Iglesias-Jimenez and Alvarez, 1993). Increases in ryegrass yields were reported at these rates and were proportional to application rate. Furthermore, MSW compost applied at approximately 45 and 90 Mg ha^{-1} to timothy and red clover forage increased yield of both crops when compared to plots with manure applications (Zheljazkov et al., 2006). Application of MSW compost at agronomic rates to cocksfoot (*Dactylis glomerata*, L.) increased yields when compared to a control and alfalfa (*Medicago sativa*, L.) yields were equivalent to the mineral fertilizer treatment (Montemurro et al., 2006). Increased yield of tomatoes grown in a fine sandy loam was increased with rates of 62 and 124 Mg ha^{-1} three consecutive years when compared to controls (Maynard, 1995) and strawberry yields were also seen to increase with the application of MSW compost when compared to composts made from other sources and fertilizer (Shanmugam, 2005). However, MSW compost proved to be a poor N-supplying amendment to corn and ryegrass where plant tissue N was lower in MSW-treated plants compared to fertilizer treatments (Iglesias-Jimenez and Alvarez, 1993; Mamo et al., 1999). It is thought that N immobilization occurs in soils treated with compost because of increased soil microbial biomass (Iglesias-Jimenez and Alvarez, 1993; Crecchio et al., 2004).

Large application rates of MSW compost (>50 Mg ha^{-1}) are often used because only a fraction of total N in compost is available to plants in the first year after application (deHaan, 1981). This practice can lead to the addition of excesses of other nutrients and trace elements. Instead, the type and ratio of feedstock and composting process should be the focus for increasing the inorganic N content of the compost when it is to be used as fertilizer. Mineralization of organic N in compost is dependent on many factors including C/N ratio of raw material, composting conditions, compost maturity, time of application, and compost quality (i.e., C/N ratio and C- and N-fractions) (Amlinger et al., 2003). The composting process is equally as important as feedstock; compost made from the same feedstock but using different technologies could differ significantly (He et al., 1995). Optimum N transformations in MSW compost were found to occur at a temperature of 55 °C, moisture content of 60%, and an air flow rate of 10 L kg^{-1} h^{-1} (Abu Qdais and Hamoda, 2004). Other research has found aeration to play a large role in the inorganic N content of MSW compost. Low oxygen levels slow decomposition and increases the opportunity for adsorption of ammonia onto the solid materials leading to immobilization (King, 1984; Korner and Stegmann, 2000; Liang et al., 2000). The concentration of nitrogen in MSW compost has been seen to increase with composting time as carbon is utilized by microorganisms (Wolkowski, 2003). Immature compost can cause N immobilization due to a high compost C/N ratio (Garcia-Gomez et al., 2003).

4.4. Phosphorus

The range of phosphorus that has been found in MSW composts is shown in Fig. 1. Municipal solid waste compost has been reported to effectively supply P to soil with soil P concentration increasing with increasing application rates (Iglesias-Jimenez et al., 1993; Zhang et al., 2006). Some reports observed that MSW compost provided equivalent amounts of P to soil as mineral fertilizers (Iglesias-Jimenez et al., 1993). Low mineralization rates of P were seen immediately after application, but after a residence time of 3 months, MSW compost provided sufficient P for plant growth (Iglesias-Jimenez et al., 1993). A 10–50% of total P in MSW compost was available both the first and second year after application (deHaan, 1981; Soumare et al., 2003). Plant uptake of P was increased with the addition of MSW compost and uptake increased with application rate; specifically strawberries, tomatoes (*Lycopersicon esculentum*, L.), spinach, ryegrass, potatoes, and Swiss chard (*Beta vulgaris*, L.) have effectively taken up P provided by MSW compost (Iglesias-Jimenez et al., 1993; Warman, 2001; Maftoun et al., 2004; Mkhabela and Warman, 2005; Zheljazkov and Warman, 2004a; Shanmugam, 2005). Soil P availability was increased with the addition of MSW compost, however, soil P retention decreased with increasing compost application because of competition between organic ligands and phosphate for sites on metallic oxides as well as the formation of phosphohumic complexes which can increase P mobility (Giusquiani et al., 1988; Iglesias-Jimenez et al., 1993). Phosphatase enzyme activity was also found to increase with the addition of low rates of MSW compost (12 and 24 Mg ha^{-1}) (Crecchio et al., 2004). Phosphatase is a P mineralizing enzyme and thus an increase in its activity may be related to the increased P availability (Stevenson, 1986). It has been concluded that MSW compost has a high capacity to supply P to plants given the compost is mature since the concentration of P in MSW compost tended to increase with composting time (Iglesias-Jimenez et al., 1993; Wolkowski, 2003).

Some research suggested that excess P was applied to soil when MSW compost was applied to meet N requirements (Bar-Tal et al., 2004). At high MSW compost application rates (>200 Mg ha^{-1}), to supply adequate N, downward movement of P was observed (Zhang et al., 2006). The P leaching potential can differ in MSW compost, depending on the feedstock used. Significantly different amounts of P leached from MSW compost taken from the same facility three consecutive years (Ring and Warman, 2000). Feedstock and compost maturity may have been responsible for these differences (Ring and Warman, 2000). Phosphorus leaching is a considerable environmental concern because the nutrient input stimulates algal and rooted aquatic plant growth and leads to accelerated eutrophication of freshwaters (Sharpley et al., 1994). Phosphorus levels in MSW compost are not regulated by the CCME or the EPA (CCME, 2005; U.S.EPA, 2000).

4.5. Potassium

A long-term study of MSW compost demonstrated that K was as available in MSW compost as in mineral K fertilizers (deHaan, 1981). The range of K found in MSW compost in the literature is shown in Fig. 1. Of the total K in MSW compost, 36–48% was found to be plant available (deHaan, 1981; Soumare et al., 2003). Soil K concentrations are increased even when very low rates of MSW compost are used (Giusquiani et al., 1988). Increased K content of the following was reported for soils treated with MSW compost: blueberries, Swiss chard, boot-stage barley, alfalfa, and cocksfoot (Warman et al., 2004; Rodd et al., 2002; Zheljazkov and Warman, 2004a; Montemurro et al., 2006; Zheljazkov et al., 2006).

4.6. Other plant essential nutrients

Many studies suggest that MSW compost is only effective at supplying N to the soil–plant system at very high applications rates (>200 Mg ha^{-1}) (Iglesias-Jimenez and Alvarez, 1993; Zhang et al., 2006). However, at these high application rates, metals in the MSW compost could become a concern. Furthermore, when discussing trace element contamination of soil, the issue of bioavailability and movement of different forms of metals must also be addressed (He et al., 1992; Zheljazkov and Warman, 2004a). The ranges of macronutrients, micronutrients, heavy metals, and trace elements found in MSW compost are shown in Figs. 1–3. Some elements of interest and concern are discussed here.

4.6.1. Calcium

A survey of selected MSW composts in the U.S. found that Ca was one of the major elements in the product, present at concentrations above 10 g kg^{-1} (He et al., 1995).

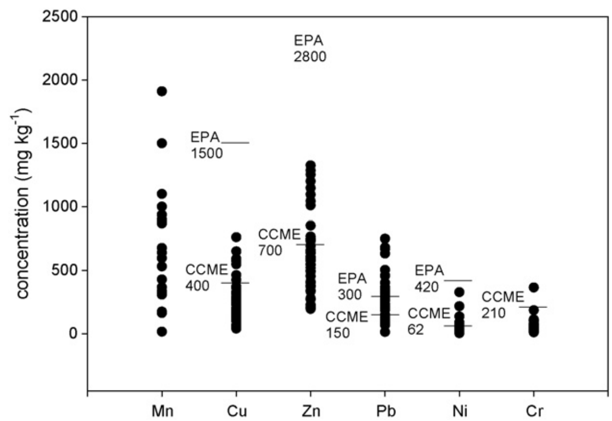

Fig. 2. Total concentrations of micronutrient and metal concentration found in MSW compost, where they apply, the Canadian Council of the Ministers of the Environment (CCME) and the Environmental Protection Agency (EPA) guideline limits are shown. Where for Mn, $n = 26$; Cu, $n = 47$; Zn, $n = 50$; Pb, $n = 45$; Ni, $n = 36$; Cr, $n = 37$ (data taken from Giusquiani et al., 1988, 1994; Hernando et al., 1989; Perucci, 1990; Iglesias-Jimenez and Alvarez, 1993; He et al., 1995; Tisdell and Breslin, 1995; Ozores-Hampton and Hanlon, 1997; Warman and Rodd, 1998; Mamo et al., 1999; Pascual et al., 1999; Pinamonti et al., 1999; Sebastiao et al., 2000; Garcia-Gil et al., 2000; Crecchio et al., 2001; Hassen et al., 2001; Hicklenton et al., 2001; Murphy and Warman, 2001; Warman, 2001; Rodd et al., 2002; Bhattacharyya et al., 2003b; Wolkowski, 2003; Garcia-Gil et al., 2004; Maftoun et al., 2004; Warman et al., 2004; Zheljazkov and Warman, 2004a,b; Brunori et al., 2005; Mkhabela and Warman, 2005; Montemurro et al., 2006; Walter et al., 2006; Zheljazkov et al., 2006).

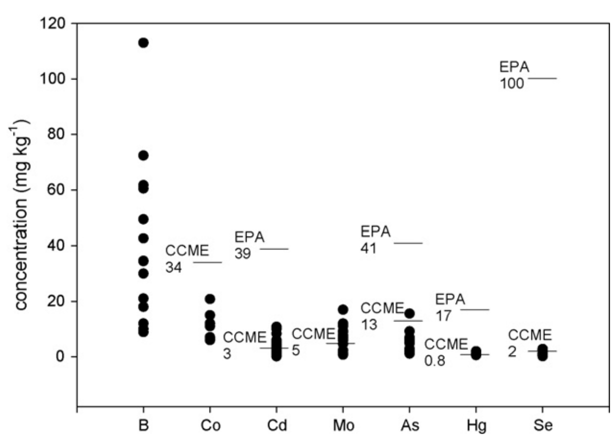

Fig. 3. Total trace metal concentrations in MSW compost. The Canadian Council of Ministers of the Environment (CCME) and Environmental Protection Agency (EPA) guideline limits are shown. Where for B, $n = 16$; Co, $n = 8$; Cd, $n = 43$; Mo, $n = 14$; As, $n = 12$; Hg, $n = 6$; Se, $n = 12$ (data taken from Giusquiani et al., 1988, 1994; Hernando et al., 1989; Perucci, 1990; Iglesias-Jimenez and Alvarez, 1993; He et al., 1995; Tisdell and Breslin, 1995; Ozores-Hampton and Hanlon, 1997; Warman and Rodd, 1998; Mamo et al., 1999; Pascual et al., 1999; Pinamonti et al., 1999; Sebastiao et al., 2000; Garcia-Gil et al., 2000; Crecchio et al., 2001; Hassen et al., 2001; Hicklenton et al., 2001; Murphy and Warman, 2001; Warman, 2001; Rodd et al., 2002; Bhattacharyya et al., 2003b; Wolkowski, 2003; Garcia-Gil et al., 2004; Maftoun et al., 2004; Warman et al., 2004; Zheljazkov and Warman, 2004a,b; Brunori et al., 2005; Mkhabela and Warman, 2005; Montemurro et al., 2006; Walter et al., 2006; Zheljazkov et al., 2006).

Municipal solid waste compost has been reported to increase total and extractable soil Ca concentrations (Maynard, 1995; Shanmugam and Warman, 2004; Warman et al., 2004; Zheljazkov and Warman, 2004a). Repeated applications for three consecutive years, progressively increased soil Ca concentrations compared to fertilizer treatments (Shanmugam, 2005). Increased soil Ca concentrations, however, did not result in increased plant uptake of Ca by blueberries, Swiss chard, and basil (*Ocimum basilicum*, L.) (Warman et al., 2004; Zheljazkov and Warman, 2004a).

4.6.2. Sulfur

Municipal solid waste compost increased soil S concentrations, but levels decreased with time perhaps due to downward movement of the element in the soil profile (Zhang et al., 2006). Increased blueberry leaf S concentrations were also seen when MSW compost was applied to an acidic sandy loam (Warman et al., 2004). Furthermore, S uptake by timothy and red clover were also increased when MSW compost was applied to plots that are submerged in water late in the spring when compared to a control (Zheljazkov et al., 2006). In both cases, the MSW compost was applied to meet the agronomic requirements of the crops. Other studies found fertilizer to increase soil S concentrations when compared to MSW compost and only weak soil S effect when MSW compost was applied (Shanmugam and Warman, 2004; Warman et al., 2004).

4.6.3. Magnesium

A survey of MSW facilities in the U.S. found that the average Mg content of MSW compost was less than 5 g kg^{-1}, ranging from 1.8 to 4.4 g kg^{-1} (He et al., 1995). Municipal solid waste compost increased total soil Mg concentrations when compared to an unamended control soil, which in turn increased Swiss chard and basil Mg concentrations (Zheljazkov and Warman, 2004a). Soil Mg concentrations were also increased when MSW compost was applied to a poorly drained soil when compared to control, fertilizer, gypsum, and manure plots (Zheljazkov et al., 2006). Magnesium concentrations in blueberry leaves were also seen to increase with MSW compost and that was proportional to the application rate (Warman et al., 2004). In another study, MSW compost was applied at 0, 50, 100, and 150 kg plant available N ha^{-1} the first year (approximately, 0, 75, 150, and 225 Mg ha^{-1}), followed by half the amount applied the following year. This study found that soil Mg concentrations increased when compared to manure applications but barley Mg concentrations appeared to decline with increased compost addition and wheat Mg (*Triticum aestivum*, L.) concentrations increased with compost application rate but declined at the highest application rate (Rodd et al., 2002).

4.6.4. Manganese

Total soil Mn concentrations tended to increase with addition of MSW compost (Giusquiani et al., 1988; Murphy and Warman, 2001; Zheljazkov and Warman, 2004a,b). The largest portion of Mn in soil treated with MSW compost was found to be bound in the iron manganese fraction, which is unavailable to plants (Zheljazkov and Warman, 2004a). Maftoun et al. (2004) also reported interactions between Fe and Mn availability. Despite its affinity for the Fe–Mn fraction, a survey of selected U.S. MSW composts found 20% of the total Mn in compost in the water-soluble fraction (He et al., 1995). There is usually a decreased plant availability of Mn as a result of MSW compost addition because of the increase in soil pH associated with MSW compost application (Warman et al., 2004). Acid soils will have a larger pool of available Mn than neutral or alkaline soils. However, the addition of MSW compost to an acidic sandy loam increased Mn in blueberry leaves (Warman et al., 2004). Increased spinach uptake of Mn due to MSW compost has also been observed despite the fact that the soil was calcareous (Maftoun et al., 2004). Gallardo-Lara et al. (2006) reported an increase in lettuce Mn and reduced Mn in barley in calcareous soil amended with the same compost. Swiss chard and basil Mn tissue concentrations decreased with MSW compost additions, that is, the highest Mn uptake was recorded at the lower application rate and lowest uptake at the highest application rate (Zheljazkov and Warman, 2004b).

4.6.5. Copper

Total and extractable soil Cu concentrations have been reported to increase when soil was amended with MSW compost and Cu has the potential to move down the soil profile (Ozores-Hampton and Hanlon, 1997; Warman et al., 2004; Zheljazkov and Warman, 2004a; Walter et al., 2006; Zhang et al., 2006). Three different soils, a neutral loam, an alkaline sandy soil, and an acidic sandy soil, were amended with two successive rates of 15 Mg ha^{-1} MSW compost and significant increases in total soil Cu concentrations were only detected in the acidic sandy soil (Sebastiao et al., 2000). Other authors found that low rates of MSW compost did not affect available soil Cu concentrations (Giusquiani et al., 1988). The largest increase of Cu in soil treated with MSW compost has been reported to occur in the organic fraction, a fraction temporarily unavailable to plants (Zheljazkov and Warman, 2004a). It has been suggested that MSW compost increased exchangeable Cu concentrations, but its bioavailability was reduced because of Cu's complexation with organic compounds, which is often increased in soils amended with MSW compost (Hernando et al., 1989; Zheljazkov and Warman, 2004a). It is suggested that only a small percentage of Cu in MSW compost is leachable (Tisdell and Breslin, 1995).

Increased plant uptake of Cu, however, has been observed in corn, potato, squash, clover, basil, and Swiss chard where plants were grown in soils amended with MSW compost (Murillo and Cabrera, 1997; Warman and Rodd, 1998; Zheljazkov and Warman, 2004a). In most cases metal concentrations remained below toxic levels. Tomato and squash fruit uptake of Cu did not occur where MSW compost was applied at a rate of 48 Mg ha^{-1} despite increases in soil Cu concentrations (Ozores-Hampton and Hanlon, 1997). The authors suggest that these crops are not Cu bioaccumulators.

4.6.6. Zinc

Municipal solid waste compost tended to increase total soil Zn concentrations when compared to unamended controls (Giusquiani et al., 1988; Pinamonti et al., 1999; Walter et al., 2006; Zhang et al., 2006). Small increases of total soil Zn concentrations were observed where MSW compost was applied at a rate of 15 Mg ha^{-1} to an alkaline sandy soil, but no increases were seen when the compost was applied to an acidic sandy soil or a neutral sandy loam (Sebastiao et al., 2000). In a pot experiment with Swiss chard, MSW compost increased total soil Zn concentration, but most of the Zn was bound in the iron–manganese fraction of the soil and plant uptake was reduced (Zheljazkov and Warman, 2004b). Furthermore, water-soluble Zn has been observed to become immobilized in soil with the addition of MSW compost (Hernando et al., 1989). Other research suggested that the biggest increase in soil Zn content appears to occur in EDTA- and DTPA-extractable Zn (Hernando et al., 1989; Pinamonti et al., 1999). It has been reported that only a small fraction of Zn in MSW compost was leachable, however, some research reported some downward movement of Zn through the profile when MSW compost was applied (Tisdell and Breslin, 1995; Zhang et al., 2006).

Zinc uptake by potatoes, Swiss chard, and basil grown in soil treated with MSW compost has been reported (Sebastiao et al., 2000; Zheljazkov and Warman, 2004a). Despite increases in available soil Zn, the Zn concentration of the tomato and squash fruit, as well as grapevines (*Vitis vinifera*, L.), however, did not increase with MSW compost additions (Ozores-Hampton and Hanlon, 1997; Pinamonti et al., 1999).

4.6.7. Iron

The range of Fe that has been detected in MSW compost is 5.3–34.9 g kg^{-1} and is shown in Fig. 1. The application of MSW compost did not tend to increase soil and plant Fe concentrations. Municipal solid waste compost applied at 100 and 35–140 Mg ha^{-1} did not increase available soil Fe concentrations nor did clover and blueberry leaves, respectively, show increased Fe concentrations compared to a control (Murillo and Cabrera, 1997; Warman, 2001). Iron basil concentrations were reduced when MSW compost was applied at rates of 200–600 Mg ha^{-1} (Zheljazkov and Warman, 2004a). Iron lettuce concentrations were reduced when 20 Mg ha^{-1} MSW compost was applied to calcareous soil but increased when 80 Mg ha^{-1} was added (Gallardo-Lara et al., 2006). Both these rates generally increased barley concentrations of Fe (Gallardo-Lara et al., 2006). Municipal solid waste compost applied to a sandy loam, however, was found to have a weak effect on available soil Fe with no effect on plant uptake and another study found significant increases in available soil Fe which increased with application rate (Maftoun et al., 2004; Warman et al., 2004).

4.6.8. Boron

Boron concentrations in MSW compost are shown in Fig. 3. Boron in MSW compost was found to be highly extractable with water and KCl (He et al., 1995). Its high mobility may cause phytotoxicity after the application of high rates of the compost but can provide B for crops that are deficient (He et al., 1995). Increased soil B concentrations were reported when 200–600 Mg ha^{-1} was applied to a sandy loam but B uptake by basil was reduced (Zheljazkov and Warman, 2004a). Increased available soil B was increased with MSW compost applications but blueberry leaf and wheat B concentrations did not increase (Rodd et al., 2002; Warman et al., 2004). Another study, however, found increased blueberry uptake of B when MSW compost was applied, but strawberries did not show uptake when the same compost was applied (Shanmugam, 2005). Other research reported the MSW compost no affect of soil B concentrations and uptake by tomatoes (Warman, 2001; Shanmugam and Warman, 2004).

4.6.9. Molybdenum

The range that Mo has been reported in MSW compost is 0.77–17 mg kg^{-1} (Fig. 3). Municipal solid waste compost increased extractable soil Mo in a gravelly loam and a sandy loam, but did not result in plant uptake by blueberries in either case (Murphy and Warman, 2001). In another study, it was shown that MSW compost increased Swiss chard Mo concentrations but no soil effect was observed (Zheljazkov and Warman, 2004a).

4.6.10. Trace elements

Total soil Pb concentrations increased with MSW compost additions (Pinamonti et al., 1999; Sebastiao et al., 2000; Walter et al., 2006). When MSW compost is applied to soil, the greatest increase of soil Pb concentrations was reported to occur in the DTPA-extractable fraction while another study observed that the greatest increase in Pb occurred in the iron–manganese fraction when MSW compost was applied (Pinamonti et al., 1999; Zheljazkov and Warman, 2004a). Only a small percentage of Pb in MSW compost is thought to be leachable (Tisdell and Breslin, 1995). Concentrations of Pb in Swiss chard, tomato, squash fruit, and basil tissues were unaffected by MSW compost amendments (Ozores-Hampton and Hanlon, 1997; Zheljazkov and Warman, 2004b). Spinach leaves amended with MSW compost were reported to take up Pb in comparison to untreated plants (Maftoun et al., 2004).

The concentrations of other trace elements in MSW compost are shown in Fig. 3. MSW compost can increase soil trace element concentrations (Pinamonti et al., 1999;

Zheljazkov and Warman, 2004a). A variety of MSW composts tested were found to have high water-soluble Ni and B, indicating potential mobility of these elements (He et al., 1995). There is conflicting evidence from field studies, where one study (Zhang et al., 2006) found soil levels of As, Be, Cd, Cr, Hg, Mo, Ni, and Se to be unaffected by MSW compost addition to an acidic loam, while another study (Pinamonti et al., 1999) found MSW compost amendments to significantly increase soil Ni, Cd, and Cr levels in neutral sandy soil. Grapevines have been reported to take up Cd, Ni, and Cr when soil was amended with MSW compost (Pinamonti et al., 1999). Municipal solid waste compost increased clover (*T. fragiferum*) Ni and Cr concentrations and Swiss chard tissue concentrations of Na, B, and Mo (Murillo and Cabrera, 1997). Tomato leaf concentration of Ni, Cd, and Pb were increased with the addition of MSW compost, as were low-bush blueberry leaf concentrations of Ni (Murphy and Warman, 2001; Warman, 2001). In some cases, despite increases in treated soils, trace metal levels in tissue and fruit remained unaffected (Ozores-Hampton and Hanlon, 1997; Zheljazkov and Warman, 2004a). Compared to other elements, Ni was present at much higher water-soluble levels in MSW compost and was considered leachable (Tisdell and Breslin, 1995). In all cases, the amounts of Ni, Pb, Cr, and Cd were below levels of phytoxicity. Most crops are harvested yearly and do not pose a risk of accumulating toxic levels of metals; however, there are plants that are metal accumulators and accumulate certain metals in their tissue well beyond requirements.

Metal and trace metal availability from compost is thought to vary with compost maturity. As compost matures, the humic material in compost tends to increase and is capable of binding many metals thus decreasing their availability (Deportes et al., 1995). The water-soluble fraction of Zn, Pb, Cu, and Cd were found to decrease and stabilize after the thermophilic stage of composting (Leita and DeNobili, 1991). The pH of compost just before the thermophilic stage was found to be acidic causing higher available Pb and Zn, which have higher water-extractable concentrations at low pH (Leita and DeNobili, 1991).

The potential for excessive amounts of trace metals to contaminate the food chain through MSW compost additions is thought to depend on the source material used in the compost and the final concentration of the metals in the compost (He et al., 1992). Municipal solid waste compost tends to have higher concentrations of metals when sewage sludge is added with the feedstock, with the lowest metal concentrations found in MSW compost which has been made from source-separated waste (Richard and Woodbury, 1992). Furthermore, the earlier the sorting of waste occurs, such as at collection or before the composting process begins, the lower the heavy metal content in the finished product (Richard and Woodbury, 1992). Bioavailability issues, however, are increasingly being considered an important variable.

The CCME decided to postpone standard limits for Fe, Al, and B because of differences in speciation and bioavailability of these elements and no precedence for these kinds of limits existed (CCME, 2005). Furthermore, the CCME guidelines explained that investigations into bioavailability of elements would be expensive and very time consuming (CCME, 2005). Currently, the United States does not have federal regulations for metal concentrations in MSW compost and the guidelines are set by individual States, if at all, guidelines are generally influenced by the United States EPA Clean Water Act 503 Regulations set for biosolids land application (Murray McBride, personal communication). Act 503 regulations include metal limits for As, Cd, Cu, Pb, Hg, Ni, Se, and Zn, and are higher levels than permitted by Canadian compost standards (Figs. 2 and 3).

4.7. Persistent organic pollutants

Few studies have reported the occurrence of organic toxins in MSW compost (Logan et al., 1999). These compounds are highly chlorinated and known to be persistent in the environment (Muir and Howard, 2006). Composting can be an effective way to reduce levels of these compounds in wastes through biodegradation, volatilization, and photolysis (Epstein, 1997). Feedstocks which contribute organic pollutants included pesticides, household wastes such as oils and solvents, and paper products because of the printing ink (Epstein, 1997). A survey of municipal and commercial wastes reported that under 0.5% by weight is hazardous and researchers indicated that phthalate esters are likely the most abundant xenobiotic present in MSW compost (Logan et al., 1999). The concentrations of dioxin/furans and polychlorinated biphenyls (PCB) were higher in mixed MSW compost than source-separated MSW compost (Logan et al., 1999). The environmental risk associated with PCB in source-separated MSW compost was deemed low (Epstein, 1997; Logan et al., 1999). A study conducted in Germany reported on the other hand, that polychlorinated dibenzo-*p*-dioxin (PCDD) and polychlorinated dibenzo-furan (PCDF) levels in MSW compost were higher than those detected in surrounding soils and were in excess of German laws (Harad et al., 1991). The authors suspect that the use of biocides were the source.

5. Recommendations

Composting of municipal solid waste has potential as a beneficial recycling tool. Its safe use in agriculture, however, depends on the production of good quality compost, specifically, compost that is mature and sufficiently low in metals and salt content. The best method of reducing metal content and improving the quality of MSW compost is early source separation, perhaps requiring separation to occur before or at curbside collection. Sewage sludge should not be added to the compost at any point since it will raise the metal content of the compost (Richard and Woodbury, 1992). A survey of MSW compost in the U.S. found that

MSW-sludge composted together showed the highest concentration of Ni, Pb, Se, and Zn, presumably because of the higher concentrations of these elements in the sludge than in the MSW compost (He et al., 1995). Copper or zinc levels may have the potential to act as indicators of sludge addition to MSW compost. The only sources of these metals in source-separated MSW compost are plant materials, animal plasma, paper, and food remains, so their concentrations in compost should remain below guideline limits (Vassilev and Braekman-Danheux, 1999).

Many researchers agree that bioavailability should be addressed in the guideline limits, in addition to metal loading. For agriculture, complete examination of metal bioavailability in soils exhibiting a range of the factors affecting plant uptake is necessary. These factors include pH, cation exchange capacity (CEC), organic matter content, soil structure, and soil texture (Pinamonti et al., 1999). Research in this area would also have to consider, and account for, the effects MSW compost may have on the soil such as, increased soil pH and organic matter content (Deportes et al., 1995; Mkhabela and Warman, 2005). A fraction of the added organic matter is resistant to decomposition but some of the humic substances eventually decompose releasing metals bound in this fraction. Rather, it is thought that the inorganic residues such as the phosphates, silicates, Fe, Al, and Mn oxide most likely provide long-term retention of metals demonstrating the need for long-term experiments (McBride, 1995). Therefore, it may be unwise to deem metals bound in the organic matter of MSW compost as unavailable for plant uptake.

A variety of plant species should also be used in trials in order to identify metal bioaccumulators to ensure that plants are safe for human consumption. Results from deep-rooting crops cannot be safely extrapolated to other shallow-rooted crops and research on a careful selection of crops should be conducted and used to develop guidelines (McBride, 1995). Furthermore, metal uptake of edible portions of crops, where the leaf is not the edible portion, should also be measured rather than leaf metal concentrations to estimate potential toxicity. While research has reported that MSW compost application did not result in metal uptake by tomato and squash fruit, this may not be the case for all fruit and vegetables (Ozores-Hampton and Hanlon, 1997).

Analytical procedures used to determine metal bioavailability also require attention. Soil Mehlich-3 (M-3) extractable soil metal concentrations were found to correlate poorly with blueberry leaf metal concentrations grown in a sandy loam in Debert, Nova Scotia, despite recommendation for M-3 use in the analysis of Nova Scotia soils (Warman et al., 2004). It is essential to identify extractants for metals that positively correlate with plant uptake of metals if metal bioavailability is to be considered in guidelines. Field studies seem to represent realistic plant–soil systems taking into account climatic factors, while greenhouse studies are generally more thorough in terms of soil and compost mixing and root exposure, but tend to overestimate metal bioavailability (McBride, 1995; Warman, 1995).

Optimization of the compost production parameters that increase nutrient availability, specifically nitrogen, need to be identified and widely used in MSW composting. Feedstock selection, aeration, and maturity are some parameters, which have been identified to influence the N content of MSW compost (King, 1984; Korner and Stegmann, 2000; Abu Qdais and Hamoda, 2004). Compost is often applied to meet N requirements of the crops and this practice often leads to the application of an excess of other nutrients because the inorganic N content of compost may be low. Adding inorganic fertilizer N to compost could solve this issue, however, the compost would then not meet organic regulations.

The physical and chemical makeup of MSW compost tends to shift with time and source and thus careful yearly monitoring of MSW compost quality is required (Hicklenton et al., 2001). Standardizing the analytical procedures used to assess quality of the final product, as well as a standardized index of compost quality need to be developed for the industry. This will allow easy monitoring of the quality of MSW compost and allow comparison of products among different facilities. To be addressed is the standard method to determine bioavailability of nutrients, metals, and trace elements in the compost and a measure of organic pollutants such as PCB that may remain in the product. Year to year variation in the properties of compost from the same source prevents researchers from drawing conclusions and inhibits research and effective use of the material (Mamo et al., 1999). Researchers and individuals using MSW compost must be assured that they are receiving a quality product consistently. Implementation of these recommendations could reduce opposition to the agricultural use of MSW compost and encourage farmers, municipalities, landscapers, and gardeners to use the product.

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