

COMPOSTING AND COMPOST UTILIZATION FOR AGRONOMIC AND CONTAINER CROPS

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Abstract

Stabilization of organic wastes by composting is highly desirable as composting eliminates odor, increases nutrient contents, and prevents the organic wastes from becoming phytotoxic when incorporated into the soil. It is a microbial-mediated process, which breaks down some of the organic N to more readily useable forms, with the release of a sizable portion of organic C as CO₂. The viability of composting depends very much on the quality and consistency of compost produced as they affect compost marketability and its end use. The article reviews the composting processes, various techniques used in compost production, and the methods used in the determination of compost maturity and quality. The selection of a technique and a location for composting should consider the availability of feed stocks and the land, and the proximity to urban population. The review also focuses in some detail on nitrogen and the ratio of carbon to nitrogen in various composts and how effective the composts are in promoting crop productivity and soil quality as well as in replacing peat as a growing medium for container crops. Because of a significant impact of compost metals on compost quality and soil metal accumulation, an extensive review was made on the concentrations of various metals in composts using municipal solid waste and/or sewage sludge (or biosolids) as feed stocks. The concentration limits of various metals in the finished composts imposed by different countries around the world and the resulting effect of compost application to soil on plant uptake of metals and the transferability of the added compost metals from soil to plants were discussed.

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I. Introduction

Increased generalization of various forms of organic wastes from diverse sources including municipality (both separated and mixed municipal refuses, digested and undigested sewage sludges, and yard wastes), animal husbandry (animal manures), and crop residues required effective means to dispose them without causing environmental impairments. With increasingly difficult to find viable landfill sites and concerns over the impact of landfill on groundwater quality, disposal of organic wastes on land is considered an attractive alternative. The practice returns nutrients back to soil for crop production, rather than burying them in the subsoil that may ultimately be transported to and contaminate groundwater by leaching. However, plants may not necessarily benefit from direct soil incorporation of unprocessed organic wastes at least within a period of time after the incorporation. Reduction in plant growth and yield is not uncommon from such a disposal practice. The offensive odor also makes it a health concern for operators who handle the wastes. Stabilization of organic wastes prior to land application is highly desirable to eliminate odor, to make nutrients in the wastes, particularly N, readily available for plant use, and to prevent the compost incorporated into the soil from being phytotoxic to plant growth.

Stabilization of organic wastes is often done with composting, which is a microbiologically mediated process. This chapter discusses the basic principles of composting, various composting methods, the degradation rate of organic matter during composting, and various methods used to evaluate the compost maturity. Also discussed are the quality of compost and the regulations imposed by various countries in the determination of compost quality. More in-depth discussion of metal concentrations of municipal solid wastes (MSW) and biosolid composts are made. Elevation of metal concentrations in compost can increase metal transfer to biota and soil accumulation of metals, thereby seriously limiting the compost utilization for crop production.

The viability of composting depends on the availability of markets for composts. Compost contains many essential nutrients and improves soil physical and chemical properties. It without a doubt is a valuable product as compost improves soil organic matter content, nutrient availability soil aeration, and water holding capacity, and reduces soil bulk density. Compost, if properly prepared, is beneficial to the productivity of field and container crops. This area of compost utilization and the use of composts as a disease suppressant are discussed in some detail.

Strategy to further improve compost quality will be continuously needed. The impacts of long-term use of composts as part of growing medium on soil and water quality have yet to be fully explored. An area where knowledge needs to be strengthened is associated with the leaching of soluble organic carbon on ground and surface water quality, availability, and translocation of compost metal, and the long-term availability of compost metal in soil. These needs are briefly discussed in this chapter.

II. The principle of composting

II-1 Composting process

Composting of manure and other organic wastes is a microbiologically mediated process with which the readily degradable organic matter in organic wastes is degraded and stabilized (Fig. 1). During the process, part of organic C is released as CO₂, part incorporated into microbial cells and part humified. The organic nitrogen primarily as protein prior to composting is mineralized to inorganic N (NH₄-N and NO₃-N), which is then re-synthesized into other forms of organic N in microbial biomass and humic substances during the composting process. Degradation of organic C during composting is carried out by bacteria, fungi, and actinomycetes, depending on the stage of degradation, the characteristics of materials, and temperature (1,2). Actinomycetes prefer moist but aerobic conditions with neutral or slightly alkaline pH. There are many thermophilic actinomycetes, which can tolerate composting temperatures in the 50s °C and low 60s °C. Actinomycetes tend to be common in the later stages of composting and can exhibit extensive growth. Bacteria are by far the most important decomposers during the most active stages of composting due to rapid growing ability on soluble substrates and tolerant of high temperatures. Thermophilic bacteria are dominant species at temperatures above 55 °C, which kill pathogens (3). Fungi have a limited role in composting. Most fungi are eliminated above 50 °C, and their optimal temperatures are much lower (4). Both bacteria and actinomycetes have a protoplasmic C:N of about 5:1, whereas fungi have approximately a 10:1 ratio (5). These microorganisms assimilate C and N in a different way. Differing nutrients available during composting will preferentially favor diverse microbial populations. Bacteria can utilize materials with narrow C:N of 10-20:1, while fungi can use materials with wide C:N of 150-200:1 (6). Although microbes are the real agents responsible for composting, their type and population size rarely are a limiting factor (7).

In the study of composting of municipal solid waste, **Hassen et al. (8)** found that high temperature during thermophilic degradation phase caused a marked change in bacterial community. *E. Coli* and faecal *Streptococci*, as well as yeasts and filamentous fungi, populations decreased sharply. *Bacilli* predominated beyond the initial mesophilic phase. Compost turning or aeration is critical for a rapid degradation and high quality compost particularly for the food waste composting (9). Although organic matter can also be degraded under anaerobic condition, the degradation is slow and less efficient, and produces less heat and more undesirable products, including CH₄ and N₂O, which are greenhouse gases contributing to global warming (10). Considering that the end use of compost is primarily for nutrient recycling and promoting plant growth, aerobic stabilization process is the preferred method of composting to produce a stabilized or mature organic amendment.

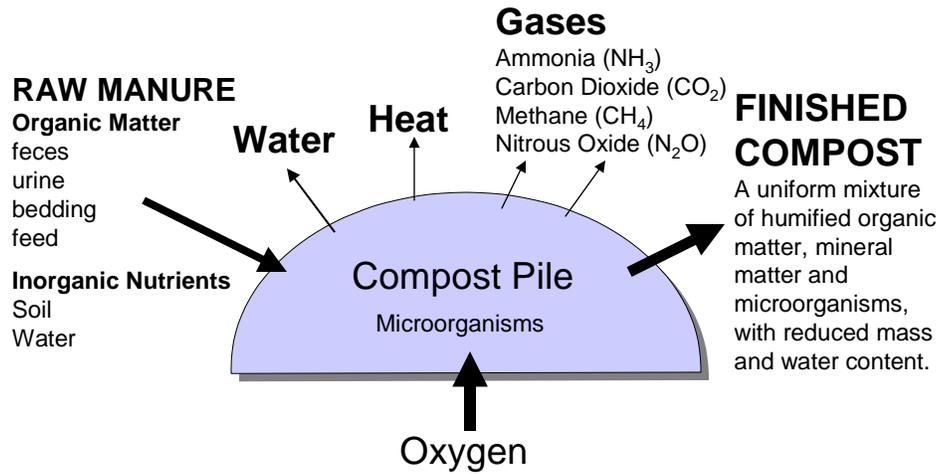


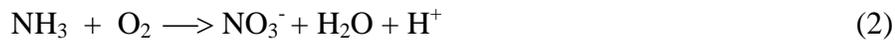
Fig. 1. The diagram illustrating the composting process for raw manure, and inputs and outputs of the composting

Heat is generated from the decomposition of organic matter. Temperature rises when sufficient heat is trapped within the compost pile. Composting can generally be divided into three stages based on the temperature in the composting pile. As the temperature of composting pile rises, the degradation quickly moves from ambient temperature into mesophilic phase, which is followed by thermophilic phase of degradation, before returning gradually back to the ambient temperature when the degradation is mostly complete or compost is mature (Fig. 2). Other major degradation products are CO₂, H₂O, and NH₃ that can be further transformed into NO₂ and then NO₃ by nitrification (Eqs. 1 and 2).

Decomposition



Nitrification



The amount of heat released during composting given by Haug (11) (Eq. 3) is expressed as follows:

$$x(H_v + H_m + H_a) = 5,866 \times \text{kg } O_2 / \text{kg compost material} \quad (3)$$

Where:

x = kg air/kg compost; H_v = Heat of vaporization;
 H_m = Heat required to heat moisture to exit temperature;
 H_a = Heat required to heat air to exit temperature.

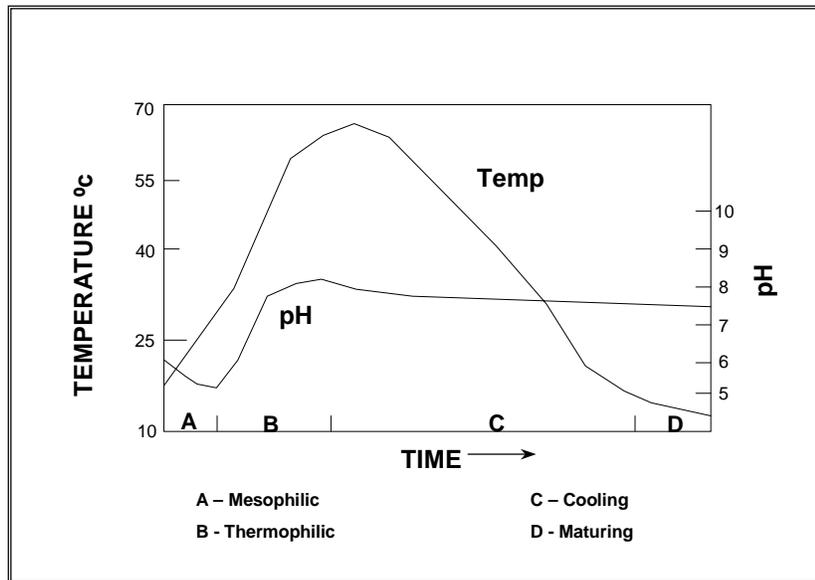


Fig 2. Changes in temperature and pH of the composting pile during composting (12).

The rise in temperature and the rate of CO_2 release from the compost are directly related to O_2 consumption rate (1) (Fig. 2). Where the amount of readily degradable C (sugars, carbohydrates, hemicellulose and cellulose) is adequate, and the compost pile is well aerated and insulated, the pile temperature will generally rise within several days to the mesophilic and then to the thermophilic phase (40° to 70°C), reflecting a vigorous microbial activity and a rapid rate of organic C degradation. The degradation by thermophilic bacteria at the thermophilic phase is critical for pathogen control and killing of fly larvae, weed seeds if the high temperature is maintained three or more days. The composting rates decrease when the temperature reaches 60°C or above (13). The temperature of the composting pile can be controlled by several strategies including configuration of the compost heap (its size and shape), by turning and watering, or by temperature feedback controlled ventilation (14).

Water is a critical factor in composting system. Microbial cells have a physiological need for water. In addition, water can function as a solvent of substrates and salts, a major heat storage medium due to its high specific heat capacity, and as temperature adjusting substances through evaporation. Theoretically, the water content of the compost could reach 100% without causing harmful effects itself. However, as water content increases, the rate of O_2 diffusion decreases. As O_2 becomes insufficient to meet the metabolic demand, the composting process slows down and become anaerobic. The upper limit of water content is between 60 and 80%, depending on the composting materials (15). The

anaerobic condition reduces the organic matter degradation rate and promotes the formation and accumulation of organic acid intermediates, and denitrification. This condition, if occurs, can be alleviated by blending more bulking agent or finished compost with the composting mixture.

A moisture level of 40 to 60% by weight should be maintained throughout the composting period (16). Although H₂O is typically added to the composting pile externally, it is also produced as organic matter in the compost is mineralized (Eq. 1). Between 0.5 and 0.6g may be produced per g of organic matter mineralized. The net loss of H₂O could occur as the heat coupled with convective transport of moisture by force aeration or turning could reduce the compost moisture to below 40% unless H₂O is added. A moisture level below 40%, while promoting aeration, restricts microbial activity. The microbial activity is severely restricted at 15% moisture level.

Coupled with the rapid rise in temperature are the depletion of O₂ if inflow of air or O₂ is restricted, increased accumulation of mineralized N as NH₄-N, and rise in pH. The accumulated NH₄-N could be volatilized as NH₃, incorporated into microbial cells if sufficient readily degradable C is available, or converted to NO₂⁻ and then to NO₃⁻ by nitrifying bacteria depending on the stage of composting and chemical characteristics of the composting pile. Reducing pH to reduce NH₃ volatilization by adjusting the pH of the compost to 6 or below is possible, but low pH interferes with the transition of mesophilic degradation to thermophilic degradation (17). The reduction of NH₃ volatilization could be accomplished by adding Mg and P salts to the composting pile at 20% of the initial N in the compost mixture to facilitate the formation of struvite (18). But the technique is not sound due to the cost associated with the application of Mg and P.

II-2 Volatile organic compounds

Volatile organic compounds (VOCs), including aliphatic and aromatic hydrocarbons, chlorinated compounds, and organic acids (e.g., formic acid, acetic acid, propionic acid, butyric acid) and sulfur-containing compounds [H₂S, COS, CH₃S, (CH₃)₂S₂, and (CH₃)₂S₃] (19, 20, 21, 22, 23) also form during the mesophilic or the early state of thermophilic phases of degradation, if the aeration of the composting pile is poor (Table 1). Total S emission as high as 8.3 mg kg⁻¹ of fresh weight of compost was found (20). High amounts of low molecular weight aliphatic acids tended to be found in the compost using straw or wood residues as feedstock (22). They are part of the degradation products of such amino acids as methionine, cysteine, histidine, tyrosine, and phenylalanine. The NH₃, organic acids, and some of the sulfur-containing compounds are odorous as the odorous threshold levels, defined as the concentration at which 50% of the population can detect an odor, are rather low (Table 2). Increased aeration can reduce the odor and promote further decomposition of intermediate compounds by thermopiles. A reduction of odor during composting can also be accomplished by not turning the compost especially during the first or second week of active (thermophilic) degradation or placing a bio-filter over the entire composting pile. Other management strategies to reduce odor emission are to decrease bulk density, and not to increase the compost pile too large and over-saturate it with H₂O. The use of electron nose (24) or a quartz crystal microbalance

that contains a number of sensors (25) may help determine timing of turning, thereby minimizing the unnecessary turnings and generation of offensive odor from the turnings.

Table 1. Odorous compounds associated with composting (26)

Compounds	Chemical formula	Boiling point	Odor
<u>Sulfur containing compounds</u>			
Hydrogen sulfide	H ₂ S	-60.7	Rotten egg
Carbon oxysulfide	COS	-50.2	Pungent
Carbon disulfide	CS ₂	46.3	Sweet
Dimethyl sulfide	(CH ₃) ₂ S	37.3	Rotten cabbage
Dimethyl disulfide	(CH ₃) ₂ S ₂	109.7	Sulfide
Dimethyl trisulfide	(CH ₃) ₂ S ₃	165.0	Sulfide
Methanethiol	CH ₃ SH	6.2	Sulfide, pungent
Ethanethio	CH ₃ CH ₂ SH	35.0	Sulfide, earthy
<u>Ammonia and nitrogen containing compounds</u>			
Ammonia	NH ₃	-33.4	Pungent, sharp
Aminomethane	(CH ₃)NH ₂	-6.3	Fishy, pungent
Dimethylamine	(CH ₃) ₂ NH	7.4	Fishy, amine
Trimethylamine	(CH ₃) ₃ N	2.9	Fishy, pungent
3-Methylindole	(C ₆ H ₅ C(CH ₃)CHNH	265.0	Feces, chocolates

Table 2. Odor threshold values (OTV) of chemicals produced from composting (27)

Chemicals	OTV (mg m ⁻³)
Methanol	73,000
1-Butanol	80
Ammonia	1
Dimethyl sulfide	0.3
Butyric acid	0.00035
Ethyl butyrate	0.00003

While many of VOCs were detected in a study of air quality in a municipal solid waste composting facility, **Eitzer (28)** showed that relatively high emission of VOCs occurred at the tipping floors where the waste is dropped off and sorted, at the shredder, and at the initial stage of composting. This posts a challenge to many of the composting facilities particularly in the tropical and subtropical regions where warm temperature and high humidity favor bacteria activity and volatilization of VOCs. In those regions, selection of appropriate composting methods to reduce the sorting and shredding times are critical to minimize emission of odor. The volatilization of organic acids (e.g., acetic acid), or odor, is reduced when the compost pile pH is raised to pH 5 or above (21). This can be accomplished by blending an appropriate amount of lime [Ca(OH)₂] with the compost. Prevention of volatilization of organic acids may be better accomplished by blending composting mix low in C:N ratio or high protein content with some lime to raise the initial pH of the compost mixture, rather than during the course of composting.

II-3 Rate of degradation of compost C

The rate of the decomposition of organic material or composting rate is generally determined by the loss of substrate, or organic C, with some imposed boundary conditions (Eqs. 4, 5, and 6). The rate when described by a first-order reaction is governed by the substrate (readily degradable C) (29) (Eq. 6). A portion of C (recalcitrant C) (Eq. 5) resistant to degradation will remain in the system. However, a lag period (t_l) (Eq. 4) is required for the microorganisms to reach a population at which active decomposition of organic matter begins. The boundary conditions for CO₂ evolution can be expressed (30) as:

$$\frac{dC}{dt} = -0 \text{ at } 0 \leq t < t_l \quad (4)$$

$$C = C_r \text{ at } t \approx \infty \quad (5)$$

$$\frac{dC}{dt} = -k(C - C_r) \text{ at } t_l \leq t \quad (6)$$

Where C is the quantity of C remaining in the composting system; C_r is the quantity of recalcitrant C in the composting system. k is rate constant. By integration, the expression of C as a function of time (Eq. 7) is given as follows.

$$C = (C_o - C_r)\exp[-k(t - t_l)] + C_r \quad (7)$$

Where C_o is the quantity of C added initially.

The percent of C loss (X_c) can be expressed in a similar fashion as follows.

$$X_c = 0 \text{ at } 0 \leq t < t_l$$

$$X_c = (1 - f_r) \{1 - \exp[-k(t - t_l)]\} \times 100 \text{ at } t_l \leq t \quad (8)$$

Where $f_r = (C_r/C_o)$

The reported values of rate constant, k , range from 0.03 h⁻¹ in the degradation of dog food (30) to 0.04 d⁻¹ in the degradation of biosolids and foodwaste (31, 32) during the thermophilic phase of degradation. The dependence of k on the degradability of substrate, the proportion of substrate in the composting mix, temperature, and aeration rate should be anticipated as these factors have bearing on the organic matter degradation rate (32, 33, 34). It is unlikely that the k value determined from one system can be extended to another system without qualification. To incorporate these parameters into the determination of k , a multiple regression technique may have to be employed.

The variation of k with temperature was found to follow the Arrhenius equation (32). The half-life of the degradation ($t_{1/2}$) (Eq. 9) can be estimated by the rate constant using the relationship as follows.

$$t_{1/2} = \ln 2/k \quad (9)$$

For Eqs. 7 and 8 to be valid, assumptions are made that the bulking agent such as sawdust has minimal degradability (30) and that its degradability is unaffected by the substrate added. This may or may not be true. Degradation of particularly hardwood sawdust is known to be enhanced by N addition (35), and C:N ratio has been considered an important parameter dictating the efficacy and duration of composting (36). This priming effect of N on C degradation, if it occurs, will contribute an error to the estimated degradation rate of the substrate. Further studies are needed to determine how N addition contributes to C mineralization of bulking agents. Without this background contribution being corrected, the degradation rate of targeted organic materials will be over-estimated to a degree depending on the extent of this contribution.

Even though the first-order kinetic equation on the average is better than zero- or second-order equation to describe the degradation of foodwaste (30), it still is a simplistic model as it does not take into consideration the population of microorganisms in the degradation of organic materials, aeration rate, ratio of organic waste to bulking agent etc. This led to the development of an empirical model to describe the degradation of vegetable waste by **Huang et al.** (34) using a non-linear regression approach. The applicability of the empirical model and coefficients generated from the study to the degradation of other organic wastes remains to be clarified.

II-4 Humic substances in compost

A reduction of carbohydrate, hemicellulose, and cellulose during the composting process is accompanied by increased humification. The humification is an index of compost maturity. It is a critical component of composting as humic substances from composting are beneficial to soil physical and chemical properties and plant productivity. Accompanying with increase in humification is increases of alkyl C, aromatic C, and carboxyl (-COOH), phenolic (-OH), and carbonyl (-CO) groups. The aromatic and phenolic C containing groups increased by 23 and 16%, respectively, following composting of municipal solid waste (37). The other major changes in the characteristics of compost are the marked increase in the content of humic acids and consequently the cation exchange capacity of compost (38), which appear to follow the first-order kinetics (38). Because of increased aromatic nature of composting product, composting process influenced not the elemental composition of finished compost but the functional groups (39).

Questions arise as to the origin of humic substances from the composting. **Adani et al.** (40) indicated that no net humic substances were formed during composting. This is in line with the findings that humic substances in the compost retain structural

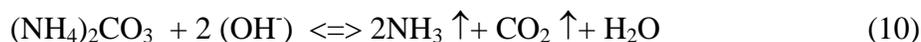
characteristics of lignin in the wood waste or crop residue used as bulking agent, and increased aromaticity of humic acids result as the protective coating materials (polysaccharides, polypeptides, and lipids) are degraded (37). The humic substances formed is dissimilar to soil humic substances (39) as they have comparatively lower concentrations of total acidity, and carboxyl and phenolic functional groups than soil humic acids (38). However, other investigators (41) found that compost humic substances are similar to soil humic substances. The question is difficult to answer, as the mechanism of humic substances production in soil and in compost is not exactly clear. If polymerization of quinones from degradation of lignin by microbial activity or polymerization of polyphenols synthesized by microorganisms is the mechanism involved in the formation of humic substances in soil and in the compost, a similarity in humic substance between soil and compost should be anticipated. However, while compost may be mature in the context of humic substances production reaching the plateau during the composting process, it will undergo further degradation once incorporated into the soil. The re-synthesis of microbial by-products over time may make the humic substances from compost before soil incorporation different from that of soil humic substances.

II-5 Compost C and N

The loss of C ranged from 46 to 62% as compared to 19 to 42% N loss during composting, depending on type of composting system, waste stream (e.g., lignin content), and composting conditions (e.g., temperature, moisture) (42). The majority of C loss is from carbohydrates, hemicellulose, and cellulose as they constitute the majority of plant C and are comparatively more easily degradable than lignin. With a much greater loss of C than N during composting especially during the active decomposition by thermophilic microorganisms, the C:N ratio of organic materials in the compost mix declines also in a first-order fashion (38) and reached a steady state after 100 days of composting of cattle manure (38, 43).

The ratio of C: N ratio of the finished compost $[(C:N)_{\text{final}}]$ to the C: N ratio of composting mix initially $[(C:N)_{\text{initial}}]$ is about 0.6 to 0.75 (44). This indicates that the C:N ratio of the initial composting mix will be reduced by 25 to 40% under normal composting conditions. The C:N ratio of compost should be about 20 to prevent N immobilization and to facilitate the release of mineral N for crop use once the compost is added to soil (35). This suggests that a C:N ratio of about 30:1 (20 to 40) (2, 12) before composting is commenced is desirable. Initial C:N ratio over 40:1 is not conducive to the degradation of organic matter due to N immobilization at least initially (35). In contrast, low C:N ratios of feedstock, or overabundance of N, tend to cause the accumulation of $\text{NH}_4\text{-N}$ as $\text{NH}_4)_2\text{CO}_3$, which at high pH levels dissociates into NH_3 and CO_2 (Eq. 10). Rise in pH (>8.5), coupled with elevated temperature in the composting pile during the thermophilic phase of degradation, promote the volatilization of odorous NH_3 . Martin and Dewes (45) found that of the total N loss during composting, a majority of it was lost by NH_3 volatilization during the thermophilic phase and the loss could be as high as 55% of total N (46). The extent of NH_3 volatilization is influenced by temperature, pH, C:N ratio, and turning (45, 46, 47). Covering the compost pile with a bio-filter comprising of wood

waste (e.g., wood chips or sawdust or finished compost) can be practiced to reduce volatilization of NH_3 , organic acids and associated bad odor from the composting pile. Control of compost pH to less than 8 is desirable as hydrolysis of NH_3 turns it to NH_4^+ , thereby reducing its partial pressure and volatilization potential.



As the thermophilic phase of degradation reaches the peak, the readily degradable organic C and O_2 in the areas of active degradation could be reduced to levels insufficient for generation of heat to compensate for the heat loss through radiation and convection. The composting pile begins to cool. Aeration at this state of composting could bring the temperature back up if sufficient readily decomposable organic C is still present. The cooling brings the composting back to mesophilic degradation and begins the stage of curing. The slow mesophilic curing process may take several weeks to months depending the feedstock, method of composting, and the extent of the degradation of degradable organic C during the thermophilic decomposition phase. This curing process carried out predominately by fungi and actinomycetes is critical as it provides time for further degradation of organic acids, huminification, and nitrification that transforms $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$ (Eq. 2), raising the ratio of $\text{NO}_3\text{-N}$ to $\text{NH}_4\text{-N}$. The ratio of $\text{NH}_4\text{-N}$ to $\text{NO}_3\text{-N}$, the ratio of humic acid to fulvic acid, and dissolved organic C content, and self heating all have been used as indexes of compost maturity, which will be discussed further. The curing process also allows colonization of compost by certain beneficial fungi for the suppression of pathogens such as *pythium*, *Rizoctonia*, and *Fusarium* when the compost is applied to the field or used in the potting mix for container crop production.

As the primary purposes of composting are to stabilize the organic wastes to facilitate recycling of nutrients in the organic wastes, and to reduce the volume of wastes going to the landfills, many types of organic wastes have been used as feedstock for composting. The wastes include sewage sludge, animal manures, yard waste, crop residues, municipal solid waste, fish scraps and mortality, and food waste and food process wastes. The materials vary widely in C:N ratios (Table 3). Since the C:N ratio of the composting mixture initially should be about 30:1(12), co-composting is feasible for some of the materials, if they are available in or near the composting facility to reduce the distance and cost of transportation. Straw from grain crop, peat moss, sawdust, wood chips and shredded and ground papers, municipal solid waste typically have high C:N ratio, and they can be blended with animal manures or biosolids for co-composting. Density of the bulking agent is related to porosity/aeration of compost and degradability of bulking agent has some bearing on N conservation (19). Passive aeration would require low bulk density to facilitate the diffusion of O_2 from the atmosphere into the interior of compost pile. The selection of a bulking agent for composting is mostly dictated by its cost and availability.

Table 3. Typical characteristics of selected raw materials (2).

Material	Type of value	% N (dry weight)	C:N ratio (weight to weight)	Moisture content % (wet weight)
Crop residue and fruit/vegetable-processing waste				
Corn cobs	Range	0.4-0.8	56-123	9-18
	Average	0.6	98	15
Corn stalks	Typical	0.6-0.8	60-73 ^a	12
Cottonseed meal	Typical	7.7	7	-
Fruit wastes	Range	0.9-2.6	20-49	62-88
	Average	1.4	40	80
Potato tops	Typical	1.5	25	-
Rice hulls	Range	0-0.4	113-1,120	7-12
	Average	0.3	121	14
Soybean meal	Typical	7.2-7.6	4-6	-
Vegetable produce	Typical	2.7	19	87
Vegetable wastes	Typical	2.5-4	11-13	-
Fish and meat processing				
Blood wastes (slaughterhouse waste and dried blood)	Typical	13-14	3-3.5	10-78
Crab and lobster wastes	Range	1.6-8.2	4.0-5.4	35-61
	Average	6.1	4.9	47
Fish-breading crumbs	Typical	2.0	28	10
Fish-processing sludge	Typical	6.8	5.2	94
Fish wastes (gurry, racks, and so on)	Range	6.5-14.2	2.6-5.0	50-81
	Average	10.6	3.6	76
Mixed slaughterhouse waste	Typical	7-10	2-4	-
Mussel wastes	Typical	3.6	2.2	63
Poultry carcasses	Typical	2.4 ^b	5	65
Shrimp wastes	Typical	9.5	3.4	78
Manure				
Broiler litter	Range	1.6-3.9	12-15 ^a	22-46
	Average	2.7	14 ^a	37
Cattle	Range	1.5-4.2	11-30	67-87
	Average	2.4	19	81
Dairy tiestall	Typical	2.7	18	79

Table 3 (continued)

Material	Type of value	% N (dry weight)	C:N ratio (weight to weight)	Moisture content % (wet weight)
Dairy freestall	Typical	3.7	13	83
Horse – general	Range	1.4-2.3	22-50	59-79
	Average	1.6	30	72
Horse – race track	Range	1.4-2.3	22-50	59-79
	Average	1.6	30	72
Laying hens	Range	4-10	3-10	62-75
	Average	8.0	6	69
Sheep	Range	1.3-3.9	13-20	60-75
	Average	2.7	16	69
Swine	Range	1.9-4.3	9-19	65-91
	Average	3.1	14	80
Turkey litter	Average	2.6	16 ^a	26
Municipal waste				
Garbage (food waste)	Typical	1.9-2.9	14-16	69
Night soil	Typical	5.5-6.5	6-10	-
Paper from domestic refuse	Typical	0.2-0.25	127-178	18-20
Refuse (mixed food, paper, etc.)	Typical	0.6-1.3	34-80	-
Sewage sludge	Range	2-6.9	5-16	72-84
	Activated sludge	Typical	5.6	6
Digested sludge	Typical	1.9	16	-
Straw				
Straw – general	Range	0.3-1.1	48-150	4-27
	Average	0.7	80	12
Straw – oat	Range	0.6-1.1	48-98	-
	Average	0.9	60	-
Straw – wheat	Range	0.3-0.5	100-150	-
	Average	0.4	127	-
Wood and paper				
Bark – hardwoods	Range	0.10-0.41	116-436	-
	Average	0.241	223	-
Bark – softwoods	Range	0.04-0.39	131-1,285	-
	Average	0.14	496	-
Corrugated cardboard	Typical	0.10	563	8
Lumbermill waste	Typical	0.13	170	-
Newsprint	Typical	0.06-0.14	398-852	3-8

Table 3. (Continued)

Material	Type of value	% N (dry weight)	C:N ratio (weight to weight)	Moisture content % (wet weight)
Paper mill sludge	Typical	0.56	54	81
Sawdust	Range	0.06-08	200-750	19-65
	Average	0.24	442	39
Wood chips	Typical	-	-	-
Wood – hardwoods (chips, shavings, and so on)	Range	0.06-0.11	451-819	-
	Average	0.09	560	-
Wood – softwoods (chips, shavings, and so on)	Range	0.04-0.23	212-1,313	-
	Average	0.09	641	-
Yard waste and other vegetation				
Grass clippings	Range	2.0-6.0	9-25	-
	Average	3.4	17	82
Leaves	Range	0.5-1.3	40-80	-
	Average	0.9	54	38
Seaweed	Range	1.2-3.0	5-27	-
	Average	1.9	17	53
Shrub trimmings	Typical	1.0	53	15
Tree trimmings	Typical	3.1	16	70
Water hyacinth – fresh	Typical	-	20-30	93

^a Estimated from ash or volatile solids data.

^b Mostly organic nitrogen.

III. Methods of composting

An adequate supply of nitrogen (N), phosphorus (P), potassium (K), and other essential nutrients in soils is essential to sustain crop productivity. Without the availability of manufactured chemical fertilizers that typically contain high analysis of N, P and K several decades ago, composting was a technique utilized by some farmers to add stabilized organic matter to soil and to convert part of organic N in animal wastes and crop residues into a more readily available form for improving soil fertility and crop productivity. The technique used is simply adding or mixing animal manure and crop residues in a static pile in a pit for several months before the compost is land applied. Crop may be planted in the same or the following season after compost addition.

The concerns over odor, phytotoxicity, nutrient availability, weed seeds, time, space, cost, metal concentration in the waste stream, and impact of composting on surface water quality in modern time have led to development of various composting techniques with different shapes and sizes, degrees of sophistications, and bulking agents used. The composting techniques including the static pile can be generally divided into three major types based on methods of aeration of the composting pile, mechanical mixing, and odor control (2).

1. Open pile processes

Static pile

- No special design for aeration
- Passive aeration

- Forced aeration
- Agitated pile
- Windrow composting
2. Reactor processes
- Vertical flow
 - Horizontal flow
 - Non-flow (batch)

Static pile is the simplest and has the least operation and capital costs compared to all other methods of composting. It, as well as the static windrow, simply involve the formation of a pile of raw materials and have a low requirement of labor and equipment. The degradable organic degrades slowly as aeration is based mainly on the passive movement of air through the pile. High porosity is needed to facilitate O₂ diffusion. To minimize the lack of O₂ inside the pile, it is recommended that the pile size should not exceed 3 m high by 4 to 4.5 m wide (48).

As the decomposition progresses, the weight loss and increase in ash content will cause the density or bulk density to increase and porosity to decrease to impede the passive movement of air through the pile. Thus, if the composting pile has a high density initially, it can create an anaerobic condition for an extended period of time especially in the interior of the compost pile. This type of composting may not raise the temperature to the thermophillic stage necessary for effectively killing pathogens, fly larvae, and/or weed seeds. This type of composting is particularly unsuited for composting putrescible food wastes. Food wastes are often rich in carbohydrates and protein, and have low C:N ratios, which are readily degradable and without adequate aeration, the decomposition will lead to formation of fatty acids and odor.

Aerating static piles can be accomplished by air suction, air blowing, alternating of suction and blowing, or temperature-controlled air blowing. Aeration in the static composting pile can be accomplished by placing a network of perforated pipes horizontally at the bottom of the composting pile. This passive aeration system allows the air to move into the composting pile by diffusion and convection as warm air within the composting pile moves upward and escapes from the top of the pile. The transport of O₂ to microorganisms in the composting pile is accomplished by diffusion and convection as indicated above and high porosity of the composting pile is required to facilitate the movement of air through the pile. Where convection is limited due to low porosity or high water saturation, anaerobic condition in some pockets can develop and composting can be uneven within the pile.

The poor aeration situation can also be reduced with mechanical agitation or turning regularly, using wheeled front-end loaders or windrow turners. Mechanical turning improves the rate of composting by increasing porosity (or air space) and distributing moisture and feedstock evenly in the composting pile. The consistency of compost increases. While windrow (or extended pile) composting is the most common composting method, the need for a large capital investment initially (including land and equipment) and a high labor requirement should be realized.

The passive aeration is not as effective as turning in the decomposition of organic matter as evidenced from the result of the analysis of CO₂ and other gases (10) in the composting of feedlot manure. The authors found that CO₂ evolution was 73.8 kg C Mg⁻¹ of manure by passive aeration as compared to 168 kg C Mg⁻¹ by turning. Passive aeration, however, had less production of CH₄ and N₂O, which are far more harmful than CO₂ in terms of global warming, than turning did (10) as turning facilitated the dissipation of CH₄ and N₂O. The passive aeration technique can be improved with the installation of a blower that forces the air through the composting pile for aeration and cooling. Forced aeration can also be made through permanent aeration outlets or channels in the concrete pad in the open field or in the bin. Improvement in the aeration in the composting pile is evident from the reduction in CH₄ production using a forced aeration system (49), but a biofilter comprising of finished compost for odor control is necessary. Accessibility to power, of course, is essential to use a forced aeration system.

None of the static composting with or without forced aeration or turned windrow composting has the capability to control the odor and leachate, particularly when composting is done in the field and without cover to protect the composting pile from rain water. Leachate particularly during the early stage of composting is enriched with dissolved organics and has high biological oxygen demands (BOD) (10,000 to 50,000 mg L⁻¹), chemical oxygen demands (COD) (15,000 to 70,000 mg L⁻¹), K (5000 to 15,000 mg L⁻¹), P (50 to 300 mg L⁻¹), and NH₃ (300 to 1,200 mg L⁻¹) (50). The deleterious impact on water quality can occur if leachate is drained into surface water. Leachate from composting should be recycled or treated to eliminate most of the contaminants before being discharged into a waterway. The drawbacks make these composting techniques unsuited in the suburban and urban environments and for composting of food wastes which typically are low in C:N ratios (Table 3) and favor high accumulation of N as NH₃. These drawbacks are largely eliminated with in-vessel composting.

There are different types of in-vessel composting systems- Bin, rectangular agitated bed (non-flow), silo (vertical plug-flow), rotating tube (horizontal plug-flow) (2, 51). In-vessel composting systems allow the operator to better control the composting process (temperature, aeration, moisture) and leachate. In-vessel composting has another advantage over the conventional windrow composting in the duration of time of thermophilic decomposition for pathogen control. Sizes and shapes of vessel depend on the size of feedstock and the degree of automation desired. Unlike large in-vessel systems, a small-scale mobile rotating drum enables the composting facility to be moved to sites where wastes are generated. The small scale in-vessel composting also can be operated as a fed-batch system (52), which composts food waste from small business or households on a continuous basis for a period of time. This reduces the waste streams going to the large composting facility and improves the quality of the compost.

The advantages and disadvantages of an in-vessel composting system should be realized before the system is utilized. The advantages include better control of the composting process and odor, less influence of weather, and less requirements for spaces and manpower. The compost produced has consistent good quality. This type of facility is

more acceptable to public especially in the suburban/urban areas where land is limited and odor is a concern, which is critical if such a facility is to be approved. Being more mechanized, in-vessel composting is more costly and requires capital expenditures and skilled labor for operation and equipment maintenance.

Another method of composting is vermicomposting, which is the process of convert organic wastes into high value organic manure using earthworms. It accelerates the mineralization rate and converts the manures into casts with higher nutritional value and degree of humification than traditional method of composting (53). Some products (agricultural and agro-industrial wastes) used to prepare vermicompost are sugarcane press mud, biodigested slurry (effluent from biogas plant), coir pith (a by-product of the coir industry), cow dung and weeds from rice. The analyses of these materials are in Table 4.

Table 4. Composition of nutrients in different organic materials used in vermicomposting (on total solid basis) (53).

Constituents	Cow dung	Biodigested slurry	Sugarcane press mud	Weeds	Coir pith
Total solid (%)	18.6	6	29	18	27
Organic C (%)	47.3	27.3	44	33	30
C:N ratio	29	15	27	25	115
Nitrogen (%)	1.65	1.78	1.61	1.30	0.26
Phosphorus (%)	0.70	0.76	1.20	0.44	0.36
Potassium (%)	0.81	0.88	0.71	0.68	0.29
Lignin (%)	-	-	-	-	29
Copper (mgkg ⁻¹)	10	11	18	20	7
Manganese (mgkg ⁻¹)	131	122	123	84	20
Zinc (mgkg ⁻¹)	54	55	84	29	19
Iron (mgkg ⁻¹)	225	193	294	125	127

Inoculation with earthworms accelerates the decomposition process, thus may help to sustain soil quality and better productivity, especially reforestation (54).

IV. Quality of Compost

IV-1. Physical factors affecting compost quality

The sustainability of composting is largely determined by its end use, health risk and consumer acceptance of the product. In essence, the compost quality or standards are driven by market development and protection of human health. To protect human health in the US, the US federal guidelines (55) limit E. Coli to less than 3 E. coli g⁻¹, and fecal coliforms to less than 1000 MPNg⁻¹, Salmonella to less than 3 MPN per 4g of total solids. Currently in the US, the finished composts are mostly for landscaping purposes, although considerable amounts are also used in agriculture and horticulture to improve soil quality and the growth of field and garden crops, and turfgrass (Table 5). When quality standards

are oriented towards marketing (or end use), compost quality standards differ from state to state within the U.S. and from country to country.

Table 5. Ranking of popular uses of compost in the United States (56)

Type of compost used	Use rank	Estimated use quantity (mT)
Landscaping	1	4,000,000
Landfill cover	2	2,000,000
Gardening and horticulture	3	1,000,000
Commercial farming	4	1,000,000

When compost quality is determined by end use, it is ranked by its physical, chemical, and biological characteristics. In the use of physical characteristic including particle size, texture, and the content of non-composable debris (stone, plastic and glass) to define compost quality, there is considerable subjectivity involved. This is reflected by the wide difference in the percent of non-decomposable debris in defining compost quality among countries (Table 6). This is true also among the states within the U.S. In the case of Canada, three standards were established based on the percentage of foreign matter (Table 7).

Table 6. Maximum foreign matter particles allowed in composts in various countries (57)

Country	Stone	Man-made foreign matter
Australia	< 5%* of > 5mm size	< 0.5% of > 2mm size
Austria	< 3% of > 11mm size	< 2% of > 2mm size
Germany	< 5% of > 5mm size	< 0.5% of > 2mm size
Netherlands	< 3% of < 5mm size	< 0.5% of > 2mm size
Switzerland	< 5% of > 5mm size	< 0.5% of > 2mm size
United Kingdom	<5% of > 2mm size	Max. 0.1% plastic < 1% of > 2mm size < 0.5% if plastic

* on a dry weight basis

Table 7. The compost class (type) based on the content of foreign matter of 2 mm in the compost (58)

	Type AA	Type A	Type B
Foreign matter content, %	<0.01	<0.5	<1.5
Foreign matter, maximum dimension, mm	12.5	12.5	25.0
Organic matter, %	50.0	40.0	30.0

For Type AA and A in the Canadian Standards, the compost is considered to be high quality, provided that their heavy metal contents do not exceed their standards, which will be further discussed later. For Type B, its use is restricted.

IV-2. Compost maturity tests

For compost to be used not for mulching but for row or container crops, its high stability or maturity is desirable as instable or immature compost is often odorous and phytotoxic, and interfere with seed germination due to the elevated concentration of NH_3 , salt content, and/or organic acids. A number of methods to test compost stability and maturity have been proposed over the last two decades with varying degrees of sophistication. Some of the methods focus on the measurement of decomposition products including temperature, CO_2 , nitrogenous products of various forms (NH_4 , NO_3 , C:N ratio), organic acids and cation exchange capacity, while others monitor the biological response to the compost (seed germination and seedling growth). The rate of the release of the decomposition products (CO_2) and the rise of temperature of composting mix are related to compost stability, whereas the biological response to compost is related to compost maturity. All these methods are listed on Table 8.

Table 8. Methods for predicting compost stability/maturity

Methods	Parameter
Physical analyses	Temperature, color
Chemical analyses	$\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, water-soluble C, C:N ratio, cation exchange capacity, Humic and fulvic acid
Microbiological assays	Respiration (CO_2 evolution; O_2 consumption)
Plant assays	Cress germination test in water extract, ryegrass growth in compost containing mixtures
Spectroscopy analyses	Solid state CPMAS ^{13}C -NMR, infrared-FTIR

Calculating the humification index by using only the carbon concentration in humic and fulvic acids can introduce mistaken values. Indeed, measuring carbon concentration alone does not take molecular structure into account. The UV method for measure the state of maturity of a compost, takes into account the non-humified fraction and the fact that the compost is young and not yet in the humification phase, making possible to approach the global chemical structure of molecules as a whole, in particular their aromatic structure. This method avoids the problem of distorted values for carbon concentration in humic acids (59). The use of spectroscopy analyses allows the determination of functional groups in the compost to explain the change to the compost composition and functional groups with time (38, 60). With increasing composting, increases in the aromaticity, alkyl C and carboxyl groups concentration, and decreases in polysaccharides and aliphatic chain results. This leads to increased cation exchange capacity of the composting mix,

which is important in terms of retention of cations following its use as soil amendment or potting mix.

As heat is released during microbial degradation of organic matter, temperature of composting mix is a good indicator of its stability. The Dewar Test (57) is often employed for the determination of compost self-heating. When the increase above ambient temperature from self-heating is less than 10 °C, the compost is classified as completely stable (Table 9). As self-heating intensifies by the further rise in temperature above ambient, the compost is increasingly immature. Being simple and easy to use, Dewar Test is used by many composting facilities around the world.

Table 9. Dewar self-heating test and CO₂ loss for determining the compost maturity (2)

Heating rise over ambient	CO ₂ loss mg C g ⁻¹ Cd ₁	Rating	Description of stability
0 to 10	0 to 2	V	Completely stable, can be stored
10 to 20	2 to 8	IV	Maturing compost, can be stored
20 to 30	8 to 15	III	Material still composting, do not store
30 to 40	15 to 25	II	Immature, active composting
40 to 50	>25	I	Fresh, very active composting

Associated with a rise in microbial activity is the release of CO₂ and consumption of O₂. The respiration rate in C loss g⁻¹d⁻¹ at 34 °C has been used in defining the class of compost (Table 9). A low respiration rate is indicative of high compost stability. However, a low respiration rate of compost may not necessarily be a good indication that phytotoxicity would not occur. This is particularly the case when microbial activity is inhibited by high metal concentration. **Wu et al. (61)** found that compost samples from one composting facility showed phytotoxicity despite having a low CO₂ evolution rate.

As composting proceeds, a greater C than N loss results in the reduction of C:N ratio (42). When C:N ratio reaches below 25:1, composting is generally considered to be mature. Despite a close relationship between the change in C:N ratio and the change in CEC or in the concentration of humic acids (38), C:N ratio alone is not a good index of maturity of composts made from a diversity of waste streams and bulking agents. The representation of compost maturity by C:N ratio can be misleading particularly when the compost contains elevated levels of NH⁺-N. This form of N is part of organic N if kjeldahl N is used to reflect organic N. While C:N ratio is an important characteristic of organic residue that determines net N mineralization and N mineralization potential (62, 63), it has not been a consistently good indicator of compost N mineralization potential. For characterization of compost maturity, C:N ratio should be used in conjunction with other stability indexes. In the Canadian Standards (CCGC) (58), the compost is deemed mature if C:N ratio is ≤ 25 and the oxygen uptake rate is ≤ 150 mg O₂ kg⁻¹ or phytotoxicity test. The CCQC also uses a two-tiered system. For composts that have C:N ratio lower than 25, it should pass one of the parameters in Group A or B (Table 10).

Table 10. CCQC proposed compost parameter tier system to determine compost maturity (57)

C:N ratio < 25	
Group A (select one)	Group B (select one)
<u>Respiration</u>	
1. CO ₂ evolution	1. NH ₄ -N:NO ₃ -N ratio
2. O ₂ consumption	2. Volatile organic acids
3. Dewar self-heating test	3. Plant test (phytotoxicity test)

Another major indicator of compost stability is the concentration of volatile organic acids (VOAs), which as indicated earlier, are produced mainly due to incomplete oxidation due to low O₂ diffusion rate relative to respiration rate. This often occurs particularly during the earlier stage of thermophilic phase of active degradation (28) when the composting material is not turned frequently enough to increase pile aeration. VOAs are a good source of C for aerobes so that VOAs often disappear if the compost pile is well aerated and if the compost pile is allowed to cure long enough. In a survey of compost maturity, **Brinton (21)** found that of the 172 compost samples, nearly 26% of the samples had VOAs greater than 5,000 mg kg⁻¹, and 6% had 20,000 mg kg⁻¹. VOAs interfere with seed germination and are phytotoxic. The total concentration of VOAs in water extract has been used as an index of compost stability (Table 11).

Table 11. Volatile organic acids (VOAs) as an indicator of compost stability (2)

VOAs rating	Concentration of VOAs, mg kg ⁻¹
Very low	<200
Medium low	200 to 1,000
Medium	1,000 to 4,000
High	4,000 to 10,000
Very high	>10,000

Phytotoxicity test (Table 12) of compost is another major index of compost maturity that is routinely conducted. The plant test includes using water extract of compost for seed germination or direct seeding into growing medium containing compost in varying proportions (57). Cress, barley, radish or lettuce has been used in the test.

Table 12. Phytotoxicity as an index of compost stability

Percent inhibition	Classification of toxicity
81 to 100	Extremely toxic
61 to 80	Highly toxic
41 to 60	Toxic
21 to 40	Moderately toxic
0 to 20	Slightly to non-toxic

Immature compost containing high VOAs is phytotoxic to seed germination and seedling growth (64). While the phytotoxicity test is of value for compost used as whole or part of growing medium for nursery crops, it may not be as useful for compost used as a soil amendment. This is because VOAs are readily degraded by soil microbes and the amount of compost added is only a small fraction of surface soil (<1%). The dilution effect could render those composts containing medium levels of VOAs less or non-toxic. This is true also for soluble salts. For use as a soil amendment, the compost does not necessarily have to have the same high quality as used for nursery container crops, many of which are sensitive to VOAs and soluble salts.

IV-3. Contaminants in composts

Contaminants in feedstock can impact the quality, marketability, and use of finished composts. Overuse and persistence of some herbicides and insecticides could result in pesticide contamination of yard waste and compost. Since composting is a biologically mediated process, there is a considerable interest in knowing if the intense biological activity during the active thermophilic degradation period could induce degradation of pesticide contaminants. In the review of pesticide occurrence and degradation during composting, Buyuksonmez et al. (65) found that a few of the targeted pesticides were found in the composts with organochlorine compounds being the most resistant to degradation during composting.

Some herbicides are resistant to degradation. Clopyralid and picloram had been detected in some compost (66). Compost contaminated with Clopyralid, a broadleaf herbicide, caused plant damage in Washington State in 1999, even though the damage largely disappears if the use of contaminated clippings as feedstock is delayed for a year or longer (67). Residues from other broadleaf herbicides for lawn care, 2,4-D (2,4-dichlorophenoxy acetic acid), dicamba (2-methoxy-3,6-dichlorobenzoic acid) and MCPP [2-(4-chloro-2-methylphenoxy) propionic acid] were detected and found toxic to tomato (*Lycopersium esculentum* L.) (68). Other pesticides that have also been detected in composts include atrazine, carbaryl, chlordane, etc. While diazinon (O,O-diethyl O-[2-isopropyl-6methyl-4-pyrimidinyl] insecticide was used extensively for insect control on turfgrass, its biodegradability is evident as only a trace of it (<1%) could be found after composting (69). Close to 11% of the insecticide was degraded during composting, and a majority of the insecticide was converted to a potentially leachable but less toxic hydrolyzed product. The release of diazinon via volatilization is extremely small (<0.2%).

Waste stream from biosolids or municipal solid waste can contain elevated concentration of various metals and the impact of metals on compost quality and use is a major concern throughout the world. The change of the chemical forms of metals during composting has been a subject of some intensive investigation. As the composting of municipal solid waste proceeds, the concentration of metals increases progressively as a result of mass

reduction due to C loss as CO₂ (70). A rapid decline of water-soluble Pb and Zn was associated with a rapid reduction of water-soluble C during composting.

The composts that use sewage sludge or biosolids or mixed or source separated municipal solid waste as waste streams in general have much higher metal content than those using animal waste as a waste stream. Attempts were made by adding natural zeolite (clinoptilolite) to the composting of municipal solid waste or biosolids to increase cation exchange capacity of the compost, thereby reducing the leachability and bioavailability of metals in the compost (71). Except for the metals in residual fraction with a high stability, compost metals in readily labile (water-soluble and exchangeable) and moderately labile forms (NaOH and NH₂OH-HCl extractable) were transferred from the compost to zeolite. However, unless zeolite is separated from the compost, metals still remain in the compost. The added cost and weight to the compost makes the practice not economically viable for composters.

IV-4. Compost metal concentration limits

To protect the quality of composts from excess contamination of metals, standards of metal concentration limits should be established. This is being done around the world, but the standards or guidelines developed are not uniform. Currently, a major difference in the maximum metal concentration limits exists between U.S. and Canada or European Union. It evolves from the fundamental difference in the approach on how to best protect human health.

In the development of guidelines for metal and metalloid concentration in compost in Canada, three approaches were considered:

1. No net degradation
2. Best achievable approach
3. No observable adverse level (NOAEL)

The basic principal of no net degradation is that the use of compost over time will not lead to increase in metal or metalloid accumulation over their background levels in the soils. The amount of metals applied should not exceed their losses through plant uptake or leaching loss. In Canada, the average metal and metalloid concentrations in soils are their background levels in uncontaminated soils in Alberta, Ontario, and Quebec Provinces plus three standard deviations. This approach was used for establishing the limits for Cd, Co, Ni, Pb, and Zn (Table 13) for two classes (Classes AA and A) of compost that are allowed for all types of applications. To encourage recycling and source separation to reduce metal concentrations in compost product, best achievable approach via source separation and reduction was used to establish the limits for As, Cr, Cu, and Hg. No net degradation approach was also taken by several European countries, and resulted in low concentration limits and the amount of metals or metalloids allowed for application to agricultural soils (Table 13). The metal or metalloid concentrations for Class B compost are far higher than those for Class AA and A, and this class of compost has a restricted use and should not be applied to food crops.

The limits developed based on no net degradation obviously is far more stringent than those based on risk assessment (Table 13). The risk-based concentrations were developed originally to regulate land application of biosolids under the section 503 of U.S. Clean Water Act (55). No observed adverse effect is the basis for the development of risk-based concentration. Numerical limit is established for each contaminant based on the analysis of the potential impacts of the contaminant on human health and environmental risks. For those contaminants that are below the concentrations limits, no restriction of the use of material is imposed as long as the annual applications of the contaminants do not exceed their annual loading limits.

Table 13. The metal and metalloid concentration limits for composts in several countries (57).

Metal or metalloids	CAN	DK	FR	GER	IT	NL	SP	US*	US**
	mg kg ⁻¹								
As	13	25	-	-	10	15	-	-	-
Cd	3	1.2	8	1.5	1.5	1	10	39	2.0
Cr	210	-	-	100	100	70	400	1200	100
Cu	100	-	-	100	300	120	450	1500	100
Pb	150	120	800	150	140	120	300	300	150
Hg	0.8	1.2	8	1	1.5	0.7	7	17	0.5
Ni	62	45	200	50	50	20	120	420	50
Zn	500	-	-	400	500	280	1100	2800	400

US* (biosolids rule); **Woods End QSAP standards

In the US, there is no uniform guideline for metal standards in compost, although a number of states utilize Biosolids Rule to set metal concentration limits for composts now. An attempt was made by US Composting Council in cooperation with the American Association of Plant Food Control Officials (AAPFCO) to setup uniform limits. Woods End Research Laboratory in Maine has recommended metal concentration limits for their QSAP (Table 13) (57) certification program, which are more in line with the European standards than with the limits in the US Biosolid Rule.

The metal partition or distribution coefficient (K_d) and metal uptake coefficient (K_f) are two important soil and plant factors included in the development of risk-based metal concentration limits by USEPA (55) based on soil-plant-human exposure pathway. Both coefficients determine the residence time and long-term accumulation of the added metals in soil. The influence of K_d , a ratio of metal concentration in solution to the concentration of the metal in soil solid phase, on leaching of the metal is expressed in the risk assessment model (Eq. 11) as:

$$K_d = \frac{C_l}{C_s} \quad (11)$$

Where C_s and C_l are concentration of contaminant in the soil solid and solution phases. The mass flux (J_{leach}) ($gcm^{-2}s^{-1}$) of the contaminant through leaching (Eq. 12) is expressed as follows, assuming no volatilization and runoff losses of the contaminant.

$$J_{leach} = C_T \rho_b (0.01V_l) / (\rho_b K_d + \theta_w) \quad (12)$$

Where C_T is total concentration of the contaminant ($mg\ kg^{-1}$), V_l is the leachate rate ($cm\ s^{-1}$), θ_w is soil water porosity, and ρ_b is soil bulk density ($g\ cm^{-3}$). The plant uptake (P_c) ($mg\ kg^{-1}$) of the contaminant (Eq. 13) is considered linearly related to the concentration of the contaminant as follows.

$$P_c = K_f C_T \quad (13)$$

Where K_f is the metal transfer or uptake coefficient. This metal uptake relationship is used in the risk assessment but its oversimplification or overgeneralization is illustrated by the fact that C_T is used as the determinant of metal accumulation by plants. The strong dependence of K_d and K_f on soil type or soil physico-chemical properties (e.g., pH) creates some concern over the metal concentration limits estimated based on this risk assessment approach. This is particularly so when soil, rather than the waste itself, has the predominant role in the uptake of metals by plants.

Obviously, the long-term accumulation of metal in soil from repeated land applications of compost or other materials and the accumulation of the metal by the plant are very much decided by K_d , which is a function of soil properties including pH, clay, organic matter, salt and soluble C contents etc., depending on the metal. A low value of K_d favors leaching and less accumulation of the metal over time and a higher concentration limit would result. A high value of K_d on the other hand will lead to a low leaching and a higher accumulation of the metal over time, which will lead to a lower concentration limit for the metal. With the concentration limit being dependent on K_d for each metal, K_d should be chosen critically, recognizing that K_d could be controlled by either the metal-contaminated material or by the soil to which the metal is added. Extending the metal concentration limit developed for one type of material to another type using the same risk analysis model is feasible if K_d and K_f are comparable between the two materials.

To overcome the overgeneralization associated with the estimate of plant uptake of metals, Hough et al. (72) proposed the use of metal concentration in soil solution to estimate metal uptake by various garden crops in their risk assessment of metal exposure to urban population subgroups subsisting on food growing on urban sites, which often are contaminated with metals due to past industrial and human activities. The advantage of this approach over that by US EPA in the prediction of plant uptake of metal is being site-specific, incorporating pH and % of organic carbon in the soil and based on the Freundlich sorption isotherm in the estimate of solution metal concentration and the uptake of metals by several vegetable crops (Eq. 14).

$$p(C_i) = \frac{p[M_c] + k_1 + k_2 pH}{n} \quad (14)$$

where M_c is the amount of metal per g of soil organic matter, k_1 and k_2 are constants, and n is the power term in the Freundlich equation. The prediction of metal uptake by the crops using Eq. (14) was found satisfactory for Cd, Cu, Ni, and Zn, but not for Pb. One should recognized that even with the inclusion of pH in the prediction of metal concentration in soil solution, it is not satisfactory as site concentration, which is often related to soil texture is not included. This is particularly important for metals (e.g., Zn) that have a high affinity with inorganic constituents of soil.

V. Utilization of Compost

In some countries, before 1980's, the soil fertility was maintained mainly by the use of organic fertilizers such as farmyard, manure, compost, green manure, straw and organic wastes (73). At the present, low soil organic matter content on arable lands has made them become less fertile (73). The over use of inorganic fertilizers and intensive field-crop production can cause the quality of agricultural soils to decline. Reduced soil physical quality is, in turn, linked to declined crop performance and/or profitability, as well as negative environmental impacts related to the off-field movement of soil (wind/water erosion) and agrochemicals (pesticide/nutrient leaching into surface and ground waters) (74). The beneficial effects of the use of compost can be seen in landscaping, which can be hard and soft landscaping schemes. Hard, includes road construction and motorway edges and surfacing of landfill sites. Soft landscaping involves the utilization of compost in parks, gardens, playground and golf courses (75).

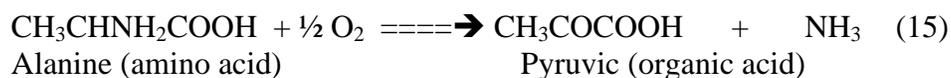
In horticulture and agriculture, compost can be used as an alternative to peat as a growing medium, as a source of organic matter, as a cover material to conserve moisture and suppress plant disease and also as a nutrient source (76).

As the quantity and quality of organic matter declines in many farming systems, farmers are now faced with finding alternative or supplementary sources of nutrients. The compound fertilizer made by compost is welcome very much at present because peasants know that too much use of inorganic fertilizers is not good to the soil and the environment (77). The variety of tropical agro-ecosystems and the diversity of organic inputs used in those systems, including trees, shrubs, cover crops and composts present a challenge for research and extension activities in soil fertility management (78).

V-1. N and C Mineralization and Compost C:N ratio

More than half N in manures or composts is organic. Organic N must be mineralized before plants can use it or it becomes susceptible to losses (79). Soil N mineralization is an important factor in the determination of soil quality (80). Nitrogen mineralization is the conversion of organic N, mostly proteins, into inorganic N such as NH_3 (or NH_4 in the presence of water) and NO_3 . It is affected by temperature and moisture availability, so

the supply of inorganic N can be expected to decrease under conditions not favorable to plant growth (81). This process also requires microbial action. Generally, microbes break down proteins into amino acids with the aid of appropriate enzymes. These amino acids, in turn, are incorporated into microbial cells, using organic carbon as the energy/substrate source. However, if the readily oxidizable C source is low relative to the amino acids, then the excess amino acids will be oxidized to NH₃ as shown in the below example (Eq. 15):



Thus, the C:N ratio of manures and manure-amended soils is important to the N mineralization process (82) being one of the important factors affecting compost quality. Values of C:N < 15:1 strongly favor this process (82). Nordstedt and Barkdoll (83) and Huang et al. (84) recommended maintaining C:N at 25 – 30:1 as the optimum ratio for composting. The C:N ratio of composted manure determines whether immobilization or mineralization will dominate in the early stages of decomposition (85).

Carbon and nitrogen mineralization can be a useful tool for quantifying the impact of various organic and inorganic amendments on soil properties (86). Their mineralization of composted manure in soils can be described by first order reaction kinetics. Nitrogen mineralization generally occurs in two phases, a rapid exponential immobilization or mineralization phase, followed by a slow linear mineralization phase. Mineralization of composted manure C is coupled with these processes in soil (85).

Carbon mineralization is generally determined by monitoring CO₂ fluxes from field-moist samples and subsequently incubated in the laboratory for various periods of time, according to the objective of the study. The rewetting dried soils may be used to equilibrate the samples before analysis (86). Rewetting dried soils is thought to alter the soil physico-chemical environment and make it an unrealistic treatment, but on the other hand, it tends to produce a uniform release of C and N and is a natural process that occurs under field conditions (86).

V-2. Compost N mineralization rate

Wide differences in mineralization depend to on pretreatment and the rate of application (87). Nitrogen mineralization from manure or compost when applied to soil depends on many factors, including (1) the properties of the organic amendment, and organic sources (e.g., C:N ratio) and its application rate and time of incubation, (2) soil properties (pH, toxic metals, moisture, temperature), (3) the incubation technique and (4) interactions between the organic amendment and the soil (88, 89). Table 14 is given as an example. Thus, site-specific studies would be required to get an accurate prediction of N supply to a crop or the potential leaching of NO₃ from organic applications.

Table 14. Net amount of organic N mineralized as effected by incubation method and amendment source during a 180 d of incubation (88).

Method*	Incubation time (days)				
	Initials (0-3)	45	90	135	180
	% of organic N				
	Poultry manure				
CC	47	45	43	44	2
BB	42	60	63	67	32
SR	43	25	47	41	33
NR	41	46	52	44	29
LI	38	68	73	83	80
	Yard waste compost				
CC	-2	1	-1	-10	-6
BB	-1	-6	-9	-2	-1
SR	-1	-2	-13	-11	-25
NR	-3	-9	-10	-9	-26
LI	-4	-12	-10	1	2

* CC: cover cylinder, BB: buried bag, SR: standard resin trap, NR: new soil-resin trap, LI: laboratory incubation

On the other hand, some general estimates of N mineralization rate have been provided to guide both growers and environmental regulators. For example, the USDA has put out a field guide of waste utilization (Table 15) with the following rates (90).

Table 15. Nitrogen mineralization rates of different manures as proposed by the USDA (90).

Manure type	Years after initial application		
	1	2	3
	% N available (accumulative)		
Fresh poultry manure	90	92	93
Fresh swine or cattle	75	79	81
Swine or cattle manure stored in cover storage	65	70	73
Effluent from lagoon or diluted waste storage pond	40	46	49

These numbers represent the high end of the N mineralization rates. It is possible that environmental regulators would be more concerned about NO₃ pollution of waters, and would use the upper-end of the N mineralization range to safely protect the environment. In contrast, a crop grower would use the lower-end of the N mineralization scale to ensure that the crops have enough N as shown in Table 16.

Table 16. Nitrogen mineralization rates of different manures (91).

Manure type	Years after initial application		
	1	2	3
Poultry floor litter	50	65	76
Dairy (fresh solids)	35	53	66
Swine manure, lagoon liquid	50	65	76

It seems that either end of the N mineralization scale can be selected, depending on philosophy and purposes. Validating the selection is needed as illustrated by some work in Japan (92) (Table 17).

Table 17. Rate of N mineralization 8-12 months after manure applications to upland rice soils in Japan (92).

Manure type	C/N ratio of manure	% N mineralized in soil
Poultry (1 year)	10.7	61
Swine (8 months)	9.8	61
Cattle (8 months)	15.8	30
Cattle (1 year)	20.3	47

There are also many mathematical models and computer programs to help predict N mineralization rate (93, 94, 95, 96, 97, 98)). One common model uses first order kinetics of the form (Eq. 15):

$$N_m = N_0[1 - e^{-kt}] \quad (15)$$

Where N_m is the amount of N mineralized at a specific time t , and N_0 is the mineralization potential at time zero, k is the rate constant. Affected by the type of compost, soil and environmental conditions, N_0 and k must be experimentally determined, usually by incubating the manure of interest with the target soil for several weeks (24 – 30 weeks), and periodically measuring the amount of $NH_4 + NO_3$ released. For example, Chae and Tabatabai (95) applied 50 ton ha^{-1} of several manures, including chicken, hog, horse, cow, and human bio-solids to five Iowa's soils and incubated the treated soils for 26 weeks. Their findings (for chicken manure) were: N_0 ranged from 456 to 758 mg N kg^{-1} , and k from 0.0033 to 0.010 d^{-1} . They concluded that soil type had marked effects on N_0 and K constants for the manures. The N mineralization percentage varied from 13 to 67% during the 26-week incubation period.

The N mineralization rate constant can be considerably lower for composts, however. It was $2.39 \times 10^{-4} d^{-1}$ for a sewage sludge compost and $2.58 \times 10^{-4} d^{-1}$ for a cattle manure composts (99). Only a small fraction (3.5%) of the total N in the composts was mineralized within the growing season. If total mineralizable N (N_0) in compost is low,

the net release of mineralized N would be small. This would require a large dose of compost to meet N requirement of crops, although such a practice leads to increased N leaching (100). The mineralization rate of compost N for the following seasons can be nearly the same (99) or substantially lower (101). It seems most likely that the compost as with manure has a readily labile pool of organic N and a resistant pool of organic N (102). The rate of the decline of compost N mineralization rate would be determined by the size of each organic N pool.

VI. Effects of compost on soils and crops

Mature compost is a brown-black crumbly material with an earthy smell and a C/N ratio of approximately 10:1. If applied to the soil, microorganisms continue to degrade the compost through a process called mineralization. This process takes place slowly in temperate climates and at increased rate under warm temperatures and moist, but not excessively wet conditions. In tropical conditions, high radiation loads and high soil temperatures eventually lead to the total disappearance of the compost leaving only the mineral nutrients behind. In temperate regions of the world, the mineralization reaction is much slower and a portion of the organic matter generally becomes stabilized as soil humus. As a result of the degradation kinetics under the two climatic regimes, annual applications may be required in tropical soils to achieve optimum benefits of the compost. In contrast, applications of compost to soils in temperate regions may result in benefits several years after their application (103).

The addition of organic matter to soil, especially in the form of compost, results in increased mineralization of nitrogen and also micronutrients (103). Application of organic by-products to soil increases soil fertility by improving the physical and chemical properties and augmenting microbial activity (and is a common way to dispose of waste). The yeast (*Saccharomyces cerevisiae*) is a by-product obtained from the recovery, processing and drying of the yeast surplus generated during the alcoholic fermentation from sugarcane. It is a product rich in proteins, carbohydrates, minerals and vitamins. Yeast amendment stimulated CO₂ production, microbial biomass and induced higher enzyme activities than in mineral fertilized or control soils (104).

Improvements in the properties of cultivated soil and increased crop production from additions of compost to soil have been reported. Smith et al. (105) reported that cabbage (*Brassica oleracea capitata*) and onion (*Allium cepa*) grown on a soil fertilized with 25% compost N + 75% NH₄NO₃-N had significantly higher yields than those fertilized with NH₄NO₃ alone (both treatments provided the same amount of total N). Similarly, Buchanan and Gliessman (106) reported that when inorganic fertilizer N was incorporated with compost, efficiency and improved crop response was higher than without compost. Higher yields of turf grass, onion, and lettuce, were observed on a sandy calcareous soil amended with a cumulative total of 37 or 74 Mg ha⁻¹ of biosolids compost over a 2-year period compared to the unamended control (107). Application of moderate additions of three sugar beet vinasse compost to a calcareous loamy sand soil had a positive effect on plant nutrition, on soil chemical fertility (soil organic matter, humic substance and Kjeldahl-N contents, and on cation exchange capacity) and yield, without serious risks of salinization or sodification of coarse textured – or well drained-

soils under irrigation (108). In Hawaii, Miyasaka et al. (109) found that organic soil amendments increased taro yield (*Colocasia esculenta*), reduced soil erosion and improved soil structure, but due to the high cost of those organic inputs, the increased yield did not result in larger profits but in losses. In Portugal, Correia Guerrero et al. (110) increased the production of fresh and dry matter lettuce (*Lactuca sativa*) planted after enriching the soil with dried orange pulp and peel wastes compost. The use of MSW compost had a moderate effect on the concentration of plant nutrients in corn (*Zea mays*) at physiological maturity. Application of 270 days MSW compost (considered mature) increased yield as MSW compost rate increased and resulted in corn grain yield near that obtained with recommended N fertilizer (111).

Manios (112) show nutritional contents of some mature compost (Table 18), and strongly recommend the mixtures of the organic wastes to ensure a good final product.

Table 18. Nutrient content of mature composts (112).

Compost	Nutrients (100 % dried matter)				
	N	P	K	Ca	Mg
<i>Unmixed</i>					
Extracted olive press cake (100%)	2.64	0.28	1.03	1.36	0.09
Olive tree leaves (100%)	2.87	0.19	0.69	8.53	0.64
Vine branches (100%)	3.74	0.29	1.4	3.17	0.61
Pig manure (100%)	2.74	0.51	0.63	11.66	1.45
<i>Mixtures</i>					
Olive tree branches with cucumber plant biomass (50%+50%, by volume)	2.43	1.39	2.59	12.59	1.82
Pig manure with olive tree leaves and vine branches (66%+17%+17% by volume)	2.85	0.29	0.82	11.55	0.92
Sewage sludge with green waste (33%+66%, by volume)	2.92	2.96	0.49	4.48	0.63

The applications of compost result in a significant increase in crop production, but the type of soil is important in determining the response of crop to compost (Tables 19 and 20).

Table 19. Effects of compost application on sorghum (*Sorghum bicolor*) yield components (5 Mg ha⁻¹) in a Ferri-gleyic lixisol (Ferrudalfs) (Southern Burkina, Africa) (113).

Treatment	Grains yield (kg ha ⁻¹)	Number of grains/panicle	1000 grains weight (g)	Straw dry matter (kg ha ⁻¹)
Compost (5 Mg ha ⁻¹)	1689	4213	25.5	5145
No compost	1160	2035	23.2	4450

Table 20. Effects of compost application on sorghum (*Sorghum bicolor*) yield components (10 Mg ha⁻¹) in a Ferric lixisol (Ferrudalfs) (Southern Burkina, Africa) (113).

Treatment	Grains yield (kg ha ⁻¹)	Number of grains/panicle	1000 grains weight (g)	Straw dry matter (kg ha ⁻¹)
Compost (10 Mg ha ⁻¹)	1380	4071	30.04	3285
No compost	408	871	31.32	2175

VII. COMPOST FOR SOIL-BORNE DISEASE SUPPRESSION

Root diseases incited by fungal and nematodes soil-borne pathogens are of common occurrence on many vegetables, including beans, onions, lettuce and carrots. The primary methods to manage fungal disease are crop rotation, host resistance, the use of chemical fungicides and nematicides as well as the use of resistant cultivars, when available. However, there has been a strong reliance on the use of agricultural chemicals for total pest control throughout the world (114). After the World War II, many farming systems in developed countries abandoned the use of crop rotation and animal manures for shortened rotations, monoculture cropping, intensive tillage, synthetic fertilizers and pesticides (115). Nematicides and pesticides are potentially toxic and have been recognized as contributing risk to human health, reduce the soil and water quality, damaging the environment, leading to an increase in plant diseases and other problems (116). In addition, nematicides must generally persist in soil for some time in order to effectively control plant-parasitic nematodes. Unfortunately, many of these nematicides have been proven to be carcinogenic, to build up in residues in food crops and to infiltrate into groundwater (114).

Composts are known to suppress plant diseases through a combination of physiochemical and biological characteristics. Physiochemical characteristics include any physical or chemical aspects of composts that reduce disease severity by directly or indirectly affecting the pathogen or host capacity for growth. Examples of these aspects include nutrient levels, organic matter, moisture, pH, and other factors. Biological characteristics include compost-inhabiting microbial populations in competition for nutrients with pathogens, antibiotic production, lytic and other extra cellular enzyme production, parasitism and predation, induction of host-mediated resistance in plants, and other interactions that decrease disease development (117).

Vallad et al. (118) have cited numerous studies of the effectiveness of composted organic amendments on various plant diseases, especially against soil-borne pathogens in container systems. The use of dried orange pulp and peel wastes compost can suppress soil-borne and foliar plant pathogens (119, 120).

Detailed review of suppression of soil-borne plant pathogens after applications of organics and especially composted organic materials has been given by various investigators (121, 122, 123, 124, 125, 126).

Improperly composted manure used in the soil of vegetable fields, revealed that *E. coli* O157:H7 can survive for more than 6 months and could be detected for at least 10 weeks on onions and 5 weeks on carrots (127). Ideally, if the composting is carried out properly, the end product should be free of most pathogenic microorganisms. However, due to the variability of environmental conditions, temperatures throughout the entire heap of composting materials may not be adequate to kill food-borne pathogens. Furthermore, during storage on the farm, the compost may be contaminated by raw manure, which can contain *E. coli* or other pathogens (127). To ensure that compost is safe to use, there is a need for limits on the content of pathogens. These limits ought to be set with respect to the potential risk posed by the pathogen as regards infection for humans, animals, and plants (128).

VIII. Compost effect on soil quality

Soil quality definition accepted by the Soil Science Society of America is “the fitness of a specific kind of soil, to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation” (129, 130).

The content and quality of soil organic matter are the most important factors maintaining the quality and fertility of soils. Land application of organic wastes and biosolids has some risks as it involves the use of complex residuals that can contain high levels of toxic constituents, for example, there may be greater risk of heavy metals entering the food chain via uptake and excess supply of P, K, and nitrates. One way of improving the quantity of applied wastes is composting, which yields an excellent product due to the accumulation of humus like substances produced from biochemical process that take place during composting. Thus, the application of composted materials to soils is expected to increase both the quantity and quality of soil organic matter (131).

Monitoring soil quality procedures include biomass and respiration measurements but extended also to nitrogen mineralization, microbial diversity and functional groups of soil fauna (132). Several parameters, including soil biological, chemical and physical properties, should be used to indicate soil quality, depending on scale and objectives of specific investigations (133). Soil quality is also consider important for the assessment of the extent of land degradation or amelioration, and for identifying practices for sustainable land use (134).

Common indicators of soil quality: To make indicator measures meaningful, decision tools must provide agronomic and environmental interpretations, reflecting both farmer and societal values (Andrews et al., 2003).

Indicators for biological soil properties: Biological properties are dynamic and sensitive to changes in soil conditions (135), and represent different aspects of soil quality in different ecosystems (136). Microbial biomass and activity are often used as indicators (137). Ratio of the respiration to biomass C, called metabolic quotient, is also used as a reliable indicator of the effects of environmental influences on the microbial population

(138). Specifically, consumption of O₂ or production of CO₂ by the treated soil is measured to indicate microbial activity (138). Chloroform fumigation and incubation is often used as a measure of microbial biomass (139). Specific enzymes and biomolecules, such as phosphatase, dehydrogenase, invertase, urease and arginine ammonification have also been suggested as indicators of soil biological activity and diversity (140). Faunal populations and the rates of litter decomposition, which includes the interaction of vegetation, soil nutrient availability, micro – and macro-fauna and microbial populations, are also considered as biological indicators of soil quality (141).

Indicators for chemical and physical soil properties: Many chemical properties directly influence biological process (e.g. via nutrient and C supply). Physical – chemical processes determine (1) the capacity of soils to hold, supply and cycle nutrients (especially, C and N), and (2) the movement and availability of water (142). As suggested by Karlen and Stott (129), soil nutrient (N, P, K, Ca, etc.) availability, soil pH, cation exchange capacity (CEC) and electrical conductivity (EC) are used as chemical indicators. Soil bulk density, aggregate stability, total and/or available water content, and soil hydraulic conductivity can also be measured as indicators of physical soil quality. Soil texture, as considered by some authors, is a master soil property that influences most other properties and processes (142).

Compost improves soil quality: Compost applications improve soil fertility over time (143, 144). The transition period between conventional and organic composted practices is often marked by a decrease in nitrogen (N) availability and in yields due to a shift in biological activity and N sources that are not immediately available for plant use (144). Soil Biological Properties: Among the benefits of composting is an increase in soil microbial activity and biological processes (144, 145, 146). Wander et al. (147) studied three farming systems: (1) animal-based (cover crops and animal manure only), (2) legume based (cover crop only), and (3) conventional (N fertilizer). Their results showed that the two organic systems had higher levels of microbial activity and more diverse species than the conventional system.

Soil Physical Properties: Organic fertility inputs (animal and/or green manures) improve soil physical properties by lowering bulk density, increasing water-holding capacity, and improving infiltration rates (144, 146, 148). Lower bulk density implies greater pore space and improved aeration, creating a more favorable environment for biological activity (146). Tester (148) also found that amending soil with compost significantly decreased bulk density and increased soil water content. Intensive field crop production can cause the physical quality of agricultural soils to decline. Reduced soil physical quality is in turn, linked to declined crop performance and/or profitability, as well as negative environmental impacts related to the off-field movement of soil (wind/water erosion) and agrochemicals (pesticide/nutrient leaching into surface and ground waters) (149).

Soil Chemical Properties: Compost increases soil organic matter (SOM) content (143, 144, 150, 151). Alvarez et al. (150) found a positive correlation between SOM content and available Ca, K, Mg, Na, and P. Obviously, total soil N will increase with organic

practices, but extractable P and exchangeable K also often do (**142, 144, 150, 151**). Wong et al. (152) found that manure compost can be an alternative to chemical fertilizer to restore the soil nutrient balance; it increases the soil macro and micronutrient for plant growth.

Knowing the ratios of humic acids (HA) to fulvic acids (FA) help to predict the possible reactions of the organic matter fraction with soil components because FAs are more soluble and reactive than HAs. This information can compliment current knowledge about compost application, making it easier to develop compost application programs that improve soil characteristics such as water and nutrient retention and soil structure (**131**).

Increasing problems concerning the environmental quality in arable landscapes and the long-term productivity of agro-ecosystems have emphasized a need to develop and improve management and strategies that maintain and protect soil function and resources. Changes in management may lead to changes in soil organic matter quantity and quality, depending on site characteristics such as soil texture (**153**). Simply measuring and reporting the response of an individual soil parameter to a given perturbation or management practice is no longer sufficient (**154**).

IX. Compost effects on container crops

Greenhouse and nursery production of plants for landscape and interior use is a specialized segment of the horticulture industry. High value crop plants are grown with the environmental inputs required for plant growth tightly controlled. (155). Container production is the norm in the nursery and greenhouse industries with almost 80% of the plants grown in containers (156). The root systems of container-grown plants are restricted to small volumes of media that must act as a reservoir for nutrients and water, provide oxygen for root respiration, and support for the plant. The growing media used in container production are typically soilless and 70 to 80% of the ingredients are organic materials (156). Container media are a foundation for the successful growing of containerized plants and their quality must be assured.

Peat, formed by the partial decomposition of sphagnums, other mosses, reeds and sedges, and bark from various softwood and hardwood tree species are the most widely used organic components of container media (157, 158). During the 1950's, sphagnum peat based media became the standard for container crop production due to peat's desirable characteristics, such as high cation exchange capacity, low bulk density, high water-holding capacity, good aeration porosity and resistance to decomposition (159, 160). But peat, a nonrenewable resource, is part of wetland ecosystems and concerns have been raised about possible detrimental effects of peat harvesting on the unique plants, animals, and insects indigenous to the wetlands. Preservation projects are increasing globally in size and in number, reducing the availability of peat resources. The current deposits of peat are derived from thousands of years of decomposition and are being replenished at only 1-4 mm a year (**159**). Peat is being consumed faster than it is being restored and limited supplies have led to increased costs. To reduce production

costs for container-plant growers and ecological damage to the peat bogs, another type of organic growing medium must be found that can serve as a replacement for peat.

Composted organic wastes have the potential to substitute for peat and bark as components of the growing media in containerized plant production systems. Most of the feedstocks used for composting are widely available and are not limited in supply. As the world's population grows, so does waste production and recycling becomes the most viable option for disposal. The container plant industry is an obvious choice for utilizing some of these recycled wastes because of its constant need for plant growth substrates. As plants are sold, the containers and the media inside are sold with them, resulting in the demand for more. Consistent quality and uniformity of compost products will be essential for their acceptance by the container plant production industry.

Physical and Chemical Properties of Container Media: In order to produce their high value crops according to schedule, growers must have a reliable source of high quality growing media that is consistent over time. From a grower's perspective, one of the major impediments to using composts for potting media is the variation in physical and chemical characteristics between different types of compost, different sources of compost, and even between different batches of the same compost from the same source (161, 162). Unlike plants grown in the field or landscape, containerized plants have very limited root-zone space, because compost in container media can comprise from 10 to 100% of the root zone, the requirements are much more stringent than those of land application and compost producers must adjust their production to meet the needs of container production (163).

Growers expect high quality and consistency when purchasing a compost product. A good growing medium is essential to the production of high quality plants. Growing media are typically mixtures of two or more components with physical and chemical properties that differ from those of the individual components. While there is no one standard growing medium recommended for all container crops under all growing conditions, there are recommended physical and chemical properties for container media (158, 164, 165, 166).

The physical properties of the media are very important in container production and porosity is one of the most important. Total porosity is defined as the percent volume of the media that is unoccupied by mineral or organic materials. It is the fraction that provides water and air to the roots, most organic media have 75 to 85% pore space (158).

Water-holding capacity or container capacity is the percent volume of media pore space that is filled with water after the media has been saturated and allowed to drain. Some of this water is so tightly bound to the media particles that it is unavailable to plants when the media dries to the permanent wilting point. A generally accepted range for water holding capacity is 20 to 60%. Dickey et al. (164) indicated that ideal container media for woody plants should have a water holding capacity of 35 to 50%.

Air-filled porosity is the percent volume of the media pore space that is filled with air after the media has been saturated with water and allowed to drain to container capacity. Often considered to be an index of media aeration, there is no precise agreement on an optimal value, there is a general consensus that 10 to 20% air-filled porosity is desirable (157). For some crops, a range of 5 to 30% air-filled porosity is considered acceptable.

The influence of container geometry on media physical properties must not be overlooked (167). Water holding capacity and air filled porosity are largely determined by container depth. Drainage is influenced by height of the media column and this depends on container size. In taller containers there is more drainage and less capacity for the media to hold water. As container height decreases water holding capacity increases and aeration decreases (158, 167). For this reason air and water-holding capacities of any growing medium should be determined in the container size that the crop will be grown.

Aeration and water-holding capacity are the media physical properties of primary interest to growers because they directly affect plant growth and cultural practices like irrigation. Particle size is another physical property of interest to container plant growers. The size distribution of the particles and pores affects the air and water holding capacities of the media. Pokorny (168) found that milled pine bark with a size distribution (by weight) of 70 to 80% of the particles in the range of 0.6 to 9.5 mm and 20 to 30% of the particles smaller than 0.6mm was very satisfactory as a container medium or medium component. This is similar to the particle size distributions recommended for hardwood bark (157, 169). Cabrera recommended that less than 20% of the particles in an organic amendment for container media be in the 2 to 10 mm diameter class, more than 60% be in the 0.5-2mm diameter class, and less than 20% be smaller than 0.5mm.

Growing media chemical properties of importance to container plant growers include pH, soluble salts content, and cation exchange capacity (158). Media pH is important because it affects nutrient availability. The pH range for plants grown in organic soils and soilless media is about 1.0 to 1.5 units lower than for mineral soils (157). The recommended pH range for most container media is 5.5 to 6.5 (166, 170). A slightly more acidic media is usually required by Ericaceous crops but the media pH should not drop below 4.5 for plants in this family (170).

Electrical conductivity (EC) is an indirect measure of the soluble salts in a growing medium. Although EC measurements vary somewhat with the method used to extract the salts from the media solution (165), an EC below $3.5 \text{ dS}\cdot\text{m}^{-1}$ determined by the saturated media extract method is generally considered satisfactory for all but the most salt sensitive plants and seedlings (157). If the 1:2 volume extraction method is used to determine soluble salts, the EC satisfactory for most plants is in the range of 0.5 to $1.8 \text{ dS}\cdot\text{m}^{-1}$. For seedlings, EC should be below $2.0 \text{ dS}\cdot\text{m}^{-1}$ using the saturated media extract and below $0.5 \text{ dS}\cdot\text{m}^{-1}$ using the 1:2 volume extraction methods (157).

Cation exchange capacity (CEC) for soilless media is expressed as milliequivalents per 100 cubic centimeters. While plants can be grown in a wide range of media irrespective

of their CECs , the medium is usually easier to manage when CEC is in the range of 6 to 15 me/100cc (158).

In summary, growers of container plants require media that have the appropriate physical and chemical properties for their crops. These media must be standardized, reproducible, available, and economical. The media must be free from diseases, pests, harmful chemicals, heavy metals and dangerous foreign materials, easy to work with and have no objectionable odor. Rynk et al. (171), and Sullivan and Miller (172) provide quality guidelines based on end use for composters aiming to produce potting grade composts.

Many types of wastes have been shown to be acceptable replacements for sphagnum peat in potting media including paper sludge compost (173), composted fishwaste (174), milled pecan shells (175), composted cotton burrs (176), and rubber tire chips (177). However, the most common composts today are derived from animal manures, municipal wastes, yard debris or trimmings, and biosolids (sewage sludge). These are all readily available, locally produced organic wastes. A number of studies have indicated that these composted organic wastes can meet growers' requirements for container media. Several investigators (166, 178, 179, 180) have reviewed the uses of composts in container production systems.

There is no single recommended amount of compost to use in growing media that applies to all situations. The amount of the compost component in a growing medium depends on the type of compost, the plant species to be grown and grower cultural practices. Bunt (157) recommends that no more than 30% by volume of compost be used in the medium.

Yard debris composts were shown to increase vinca (181), chrysanthemum and fuchsia growth as compost percentages in the media increased (182). Spiers and Fietje (183) suggested that composted leaves and woody materials could be a component of high quality growing media, but should only be used up to 30% of the volume to avoid phytotoxicity due to high soluble salts. Beeson Jr. (184) found azalea plants grew larger than control plants in a pine, peat and sand mix when 40% composted yard debris replaced peat in the potting media

Biosolids were an effective peat substitute for marigolds when cocomposted with sawdust (185) and increased growth of *Photinia* and *Thuja* was observed when biosolids compost as a medium component was increased from 25% to 50% (186). Different plant species may show more consistent performance in biosolids compost than comparable composts made from other waste streams (187). A variety of annuals, perennials, and woody ornamental plants performed best in 50% and 100% biosolids compost (187).

The greenhouse industry applies more fertilizer per unit area than other agricultural systems (188). However, fertilizer applications can be reduced when composts with high nutrient concentrations are substituted for peat. Even when fertilizer is added to media containing composts, plant growth increases are usually not as dramatic as the growth increase seen when fertilizer is added to conventional media (189). According to Jespersen & Willumsen (190), compost is suitable to replace peat up to 20-40% by

volume and to replace most of the fertilizer used in commercial peat growing mixes. Fishwaste compost was found to provide enough available nitrogen for seven weeks after marigolds were transplanted (174).

Chaney et al. (191) used a peat-vermiculite medium that required addition of N, P and trace elements for proper growth. These nutrients were deleted one at a time, all, or all but N. Digested biosolids compost was added at various rates to this peat mix and marigold growth was analyzed. It was determined that the addition of 33% compost provided all trace element requirements, corrected phosphorus and copper deficiencies and produced suitable plant growth with only the addition of nitrogen. Falahi-Ardakani et al. (192) grew several vegetable species in composted biosolids used at 1/3 by volume and found adequate phosphorus, calcium and magnesium, and trace elements were supplied for 5 weeks of growth. Marcotrigiano et al. (193) showed that species responses varied, but the biosolids provided high levels of nutrients and could replace fertilizer applications for short-term crop production. Only N was needed to produce marketable plants when lettuce and tomato transplants were grown in a mix consisting of composted biosolids, peat and vermiculite (194).

In some cases, it may be possible to reduce or eliminate fungicide applications by utilizing composts in growing media (161). Many types of soil-borne pathogens commonly found in soilless potting media can cause disease and decreased yields (195). Composts have been found to suppress these pathogens and reduce the incidence of damage but the degree of suppression is dependent upon the maturity and type of compost (196, 197, 198). Some composts naturally support the microorganisms that can monopolize food sources and out-compete the pathogen spores, while others need to be inoculated after the heating process to suppress specific pathogens (198).

A number of problems have been documented when composts were used as growing media. High soluble salts in composts can be a problem for a variety of plants, ranging from salt sensitive to non-sensitive species (166, 179, 180, 183, 189). Nitrogen immobilization (181) as well as phototoxicity caused by compost immaturity, nutrient toxicity or deficiency can cause problems for plants grown in composts (166).

Many different plant species and cultivars are grown as nursery and greenhouse crops and they react differently to various types and amounts of composts. Depending on the compost, some plants grow well in 100% compost by volume, while others may perform best when the volume is below 30%.

A wide range of recycled organic waste composts are being produced and some show greater potential as container media than others. But the preponderance of research studies indicates that high quality composts have great potential serve as organic components of soilless growing media. Composts have been shown to reduce fertilizer applications due to their slowly released supply of macro- and micronutrients, increase water-holding capacity, and to suppress soil-borne pathogens thereby decreasing the need for fungicide applications.

X. Compost metals

The concerns over metal accumulation from compost application are phytotoxicity, increased human exposure to metals, and the ecological health of soil. Of the metals to be of concern are As, Cd, Pb, Cr, Cu, Ni and Zn. While all of the metals are phytotoxic if present in elevated concentrations in soil, the first four metals are highly toxic to human health. Since soil is central to the transfer of the metals to the plants, animal and humans, limiting their excess accumulations in soils is fundamental to the compost utilization and management. This has led to the establishment of metal concentration limits for composts in some countries discussed earlier.

Closely examining the metal inputs and outputs is key to what soil metal concentration might be in the long term. The inputs of metals into soils can be from diverse sources including aerial deposition particularly near smelters and land application of metal-contaminated organic amendments (compost, animal wastes, sewage sludge) and fertilizers (Fig. 3). The outputs are plant uptake, leaching/runoff, volatilization (Hg and As), and removal of surface soil by excavation (Fig. 3). If the inputs were equals to outputs, metal concentration in soil would remain the same, which is the principle of no net degradation approach in establishing metal concentration limits by some countries. Whether the metal concentration limits of composts are developed based on no net degradation or no observable adverse level, knowledge of metal concentrations and application rate of compost and metal utilization or uptake by plant are critical since they largely determine the net input of metals in the soils where leaching and runoff loss of metals are minimal.

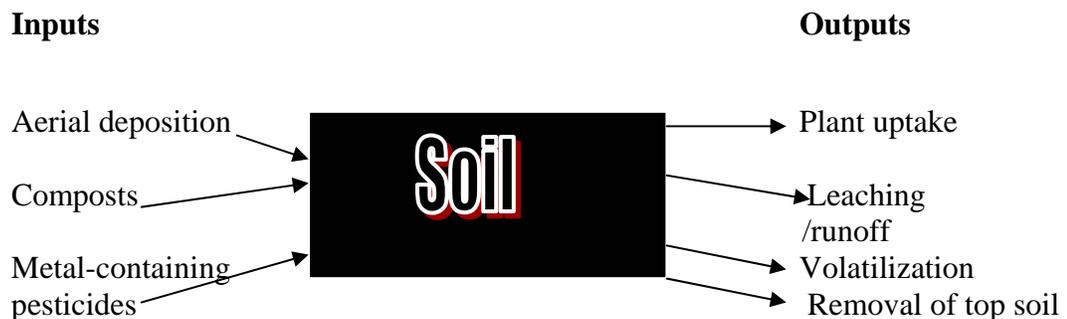


Fig. 3. Inputs and outputs of metals in soil

X-1. Compost metal concentrations

Compost metal concentrations vary depending largely on the metal concentrations in the feedstock. Metal concentrations in the finished composts tends to be higher than in the initial composting mix as a result of compost weight loss by degradation of organic matter (70). The concentration of metals in the finished compost may be higher or lower than the feedstock depending on the type of bulking agent used. It should be lower if

sawdust or straw is used to compost with biosolids (Table 3), but it may be higher if mixed municipal waste is used. While straw or sawdust is typically low in metal concentration, mixed municipal solid wastes may contain metal (e.g., Pb) concentration even higher than biosolids.

Table 21 shows the range and mean concentrations of some metals for some municipal and biosolids composts in the US. The wide variations in the concentration of the metals among the MSW or biosolids composts reflect the difference in metal concentration in the feedstock, bulking agent and/or composting method used (1). The data show that biosolids compost on the average has higher metal concentrations than MSW compost. The concentrations of the metals in these types of composts generally are far greater than yard waste debris or animal manure compost with the exception of compost from manure of animal fed with feeds enriched with Cu and/or Zn as additives (199, 200, 201). The concentration of Cu and Zn in some swine manure composts reached as high as 1380 and 2840 mg kg⁻¹, respectively.

Table 21. The concentrations of metals in some biosolids and MSW composts.

Metal	MSW compost			Biosolids compost		
	Range	Mean	n	Range	Mean	n
Cd	0.6-11	3.7 (2.5)	12	2.0-16	6.7(4.4)	8
Cr	0.1-186	70.0(48)	13	45.0-578	163.0(174)	8
Cu	36.0-762	308.0(194)	13	180.0-890	401.0(217)	8
Ni	5.1-80	45.0(45)	14	15.0-350	74.0(112)	8
Pb	24.0-603	281.0(172)	14	14.0-863	347.0(321)	8
Zn	38.0-1420	715.0(396)	14	116.0-1801	898.0(462)	8

Values within the parenthesis are standard deviations

The concentrations of Cd, Cu, Ni, Cr, and Pb in the MSW and biosolids composts in the US are highly correlated with the average annual consumption of the metals by the US over a span of 20 years (1970 to 1990) for Cd, Cr, Cu, Pb, Ni, and Zn. The average annual consumption rates for the metals were calculated using data from USGS for Cd (202), Cu (203), Cr (204), Pb (205), Ni (206) and Zn (207). The coefficient of determination (r^2) was high, 0.90 for the MSW compost and 0.92 for the biosolid compost (solid triangles) (Figs. 4 and 5), when Zn (open triangle) was excluded in the regression. A fraction of the metals used in the manufacturing of various products ends up in the waste streams. The deviation of Zn from the other metals in the relationship signals a far greater amount of Zn entering the waste streams than the other metals at the same amount of consumption annually. This perhaps is related to the extensive use of Zn in agriculture, and consumer goods including anti-corrosion coatings on steel, construction material, brass, pharmaceuticals and cosmetics, tires, micronutrient for humans, animal, and plants. Zinc would have a greater probability to enter the waste streams. It is anticipated that the magnitude and direction of flows of the metals in the whole ecosystem vary with metal and detailed analysis of the structure of the flows of metal as was done for Pb by Socolow et al. (208) should be encouraged to quantify the amount of the metals which could end up in the waste stream annually. The magnitude of each flow in a region will likely to be affected by its social and economical conditions,

regulations and by season, as well. The structure of the flows could help explain the regional differences in the concentrations of metals in the MSW and biosolids composts.

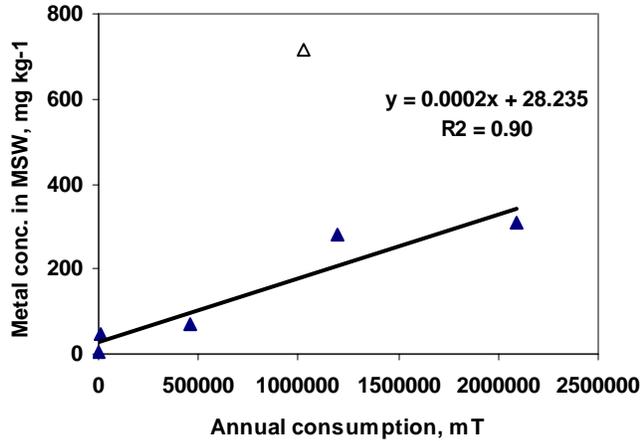


Fig. 4. The relationship between the concentrations of Cd, Cu, Cr, Ni, Pb (solid triangle), Zn (open triangle) in the MSW compost and their annual consumption in the US. Zn was considered outlier in the regression analysis.

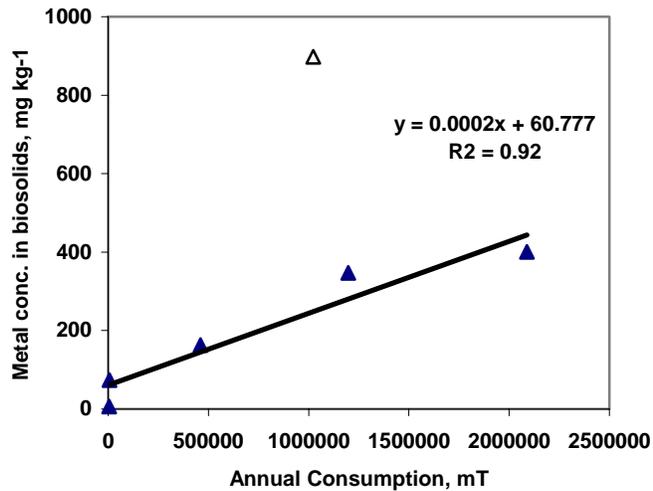


Fig. 5. The relationship between the concentrations of Cd, Cu, Cr, Ni, Pb (solid triangle), Zn (open triangle) in the biosolids compost and their annual consumption in the US. Zn was considered outlier in the regression analysis.

Reduction of metals in the waste streams before the wastes are composted is one avenue to lower metal concentration in MSW and biosolids composts. This leads to source

separation either at the central collection facility and/or at the origin of the waste source. The success of source separation to lower the metal concentration in the compost is evidenced by a much lower metal concentration for the source separated MSW compost than for the mixed MSW compost (Fig. 6) (209). Source separation in essence modifies the structure of the flows when non-compostable metals are taken out from the flow to the waste stream to the flow of recycling. Source separation of MSW should be encouraged before MSW is composted. This would reduce the entry of metals into the soil when compost is applied to soil for mulching or for improving soil physico-chemical and microbiological properties.

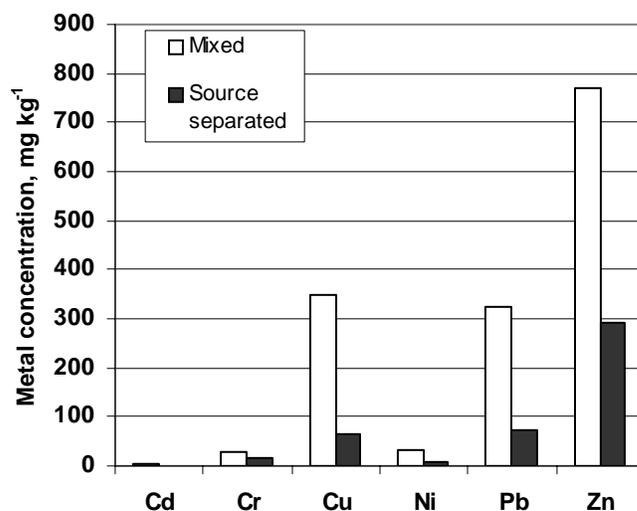


Fig. 6. The concentration of metals in the mixed MSW compost and in the source separated compost (209)

X-2. Forms and mobilization of compost metals

Because of the impact of compost metals on metal accumulation in soil and in plant, investigations were made to the forms and solubility of metals particularly in the MSW and biosolids composts, and in the metal-enriched swine manure composts. Compost itself is comprised of organic and inorganic components, and metals in the compost are likely to distribute in the two components in magnitudes depending on the affinities of the metals with organic and inorganic constituents, and redox conditions of the compost. The typical method to study forms of metals in compost is using sequential extractions. Compost is sequentially extracted with KNO_3 (0.5 M), H_2O , NaOH (0.5 M), EDTA (0.05 M), and HNO_3 (4 M) to separate compost metals into operationally defined fractions as exchangeable, water soluble, bound to organic, precipitated as inorganic (carbonate and sulfide precipitates), and residual metals (210, 211, 212). Being an excellent chelator of the metals with a stability constant ranging from 16.46 for complex Cd to 23.4 for complex with Cr(III), it is not surprising that a large fraction of the metals in compost can be extracted with EDTA. Another extraction scheme by sequentially extracting compost with MgCl_2 (1 M) (exchangeable), sodium acetate (1 M) (carbonate bound),

hydroxylamine hydrochloride $[\text{NH}_2(\text{OH})\text{HCl}]$ (0.04 M) (bound to Fe and Mn oxides), HNO_3 (0.02 M)– H_2O_2 (bound to organic matter), and HF – H_3BO_3 or HNO_3 – HClO_4 (residual) was also extensively used (201, 213, 214, 215). Using the latter extraction scheme, Tisdell and Breslin (213) showed a comparatively high exchangeability of Cd in MSW composts (> 10%) and the exchangeability of some MSW compost metals decreased in an order as follows.

$$\text{Cd} > \text{Zn} > \text{Ni} > \text{Cu} > \text{Cr} \cong \text{Pb}$$

A high exchangeability of Cd and Zn was also found in biosolids compost (216).

The sequential extractions also show high percentage of compost Cu in organic, high compost Cr in the residual fraction, and high compost Zn in the Mn and Fe oxides components of the compost (Fig. 7). A high percentage of Pb is in organic, and Fe and Mn oxide fractions. The highly inorganic nature of Zn in MSW compost is reflected by more than 70% of total Zn in inorganic fractions (Exchangeable + carbonate bound + Fe and Mn oxides bound). Hsu and Lo (201) also found the same high percentage of Zn in swine manure compost in the inorganic fractions, although the percentage of Cu in the swine manure compost was not as high as in the MSW compost. Differences among composts in the percentage of the metals associated in various fractions are to be anticipated as compost may vary in the contents of lime, Fe and Mn oxide, organic matter, maturity, and particle size. Metals tend to be more concentrated in the fine particle size (<1 mm) with an average enrichment of 1.30 ± 0.11 (SD) across Pb, Cu, Zn, Cd, Ni, and Cr (210).

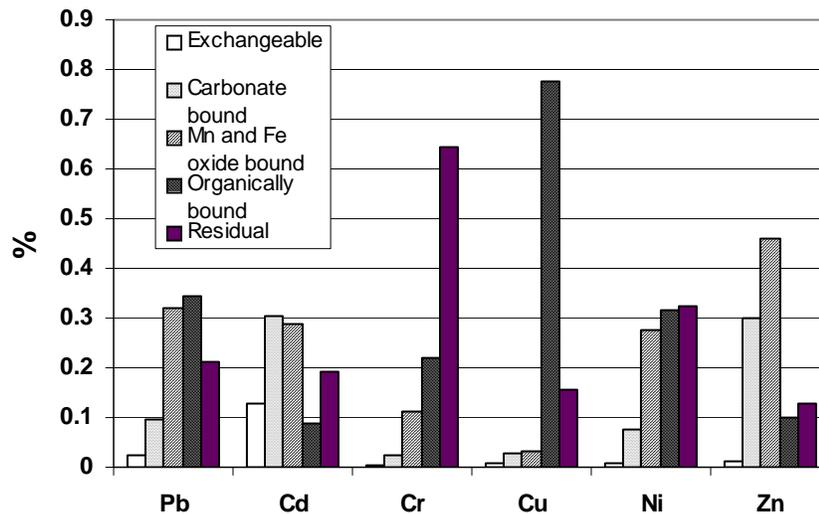


Fig. 7. The sequential extraction of metals in MSW compost (213)

Sequential extractions of metals in compost or compost-amended soil give some clue as to the labilities and stabilities of compost metals. The higher the percentage of compost metals in the exchangeable form, the greater the lability or mobility of the metal (211,

214). Sequential extractions are also useful for tracking the change in lability and transformation of compost metals over time. Their other use for predicting the availability of compost metals is handicapped by the lack of the knowledge of how the moderately-labile (carbonate, Fe and Mn oxides, organic matter bound) and non-labile (residual or structure-bound) fractions of compost metals influence the pool size of the labile exchangeable metal fraction.

Mobilization of compost metals through leaching or surface runoff is of concern to water quality. Although the amount of Cd, Cu, Ni, and Zn leached from the container-growing medium amended with MSW compost has been shown to be very small relative to the total input of the metals from the compost (217), the increase in the amount of the metals leached with increasing proportion of the compost or compost metal in the growing medium indicates that the quantity of compost metal input in the growing medium is a factor in the mobilization of compost metals. The extent of metal mobility, however, is more likely to be controlled by the concentration of SOC, particularly the light molecular weight soluble C (polysaccharides, amino acids), and pH level than by the total amount of compost metals in growing medium. This is because of the high chelation ability of SOC and the ionization of its function groups such as carboxyl ($-\text{COOH}$) and phenolic ($-\text{C-OH}$) on SOC, and hydroxyl ($-\text{OH}$) on the oxide or other solid surface is pH-dependent. High correlations of SOC with dissolved Zn and Pb (70) and with dissolved Cu in compost and in soil solution (201, 218) have been shown. The impact of solution pH on solubilization and mobilization of compost metals is not the same among all targeted or non-targeted metals. The solubility of Cd, Cr, Co, Ni, Pb, and/or Zn did not significantly increased with increasing pH of yard-waste biosolids compost (201, 215). For Cu, a parallel increase in Cu and SOC when solution pH was increased to above 7 (201) signaled a high affinity of Cu with SOC and increased negative charge of Cu-SOC complex as solution pH was raised above 7. The conditional stability constants ($\log K^c$) for the binding of Cu with $-\text{COOH}$ functional group for SOC from one-week decomposition of wheat and crimson clover residues was 6.8 to 7.0 (pH 5.5 to 6.0; ionic strength 0.1 to 0.01 M), and the average binding capacity was 0.45 mmol Cu kg^{-1}C (219). The complex of Cu with SOC could become progressively negatively charged as solution pH level was raised above 7 and excluded from the surfaces by electrostatic repulsion.

As solution pH is increased, deprotonation of $-\text{OH}$ functional groups on the surface of such minerals as Fe oxide also creates new metal sorption sites. This results in a greater metal sorption capacity by the minerals (220). The net effect of solution pH on metal solubility will hinge on whether or not metal-SOC complex is more stable than the binding strength of the metal with charged mineral surfaces. For the metal such as Cu, the stability of its complex with SOC apparently is greater than the binding strength of Cu with the charged oxide surfaces to result in a greater solubility and mobility of Cu at high SOC concentrations particularly at the early stage of composting and high pH levels.

Increased humification or polymerization of low molecular weight compost SOC as degradation of organic matter or composting progresses increases its binding capacity and strength of metal (Cu) (219). This explains the increased stability of compost metals

with increasing maturity of the compost. However, there are findings related to the association of metals with organic constituent in the compost that are difficult to explain. Petruzzalli et al. (221) showed that nearly all of the compost Cu, Zn, Cd, and Cr, and more than half of compost Pb, in organic matter fraction is associated non-humic fraction. The sequential extractions of MSW composts by He et al. (222), however, showed that more Cr and Cu in the composts were recovered in HA than in FA fraction, but more Pb and Cd in FA than in HA fraction. Continuous monitoring of the change with time of compost metals associated with fulvic acid, humic acid and non-fulvic fractions would have to be made to address whether or not further polymerization of SOC shifts the metals it adsorb from fulvic to humic acid fraction.

X-3. Effects of Compost Application on metal accumulation in soil and plant uptake

Whether or not the application of compost to soil will increase soil accumulation of metal depends on if a net input of metal occurs. The net input is the difference between the total metal inputs from all sources including compost applications and outputs via plant uptake, leaching and surface runoff. The leaching of compost metal in soil relative to the total compost metal input was rather small (217, 223, 224). This was true even for Cu that forms a stable complex with SOC. Although the mobility of soil metal is often mediated by SOC, large amounts of compost metals leached beyond the plow layer is not expected. Nearly all of SOC added to soil or forest floor from compost is retained by soil (224, 225). Unless the soil is situated near a smelter or power plant receiving excess deposition of metal-contaminated particulate matter, the net metal input in the soil is presumed to be the difference between metal input from compost application and metal output in the harvested plant materials.

Increased accumulation of Cd, Cu, Ni, Pb and Zn in the soil was noted with increasing application rates of biosolid or MSW compost (211, 223, 226, 227). The increase was essentially linear. The result was true also for even the source-separated MSW compost (228) (Fig. 8).

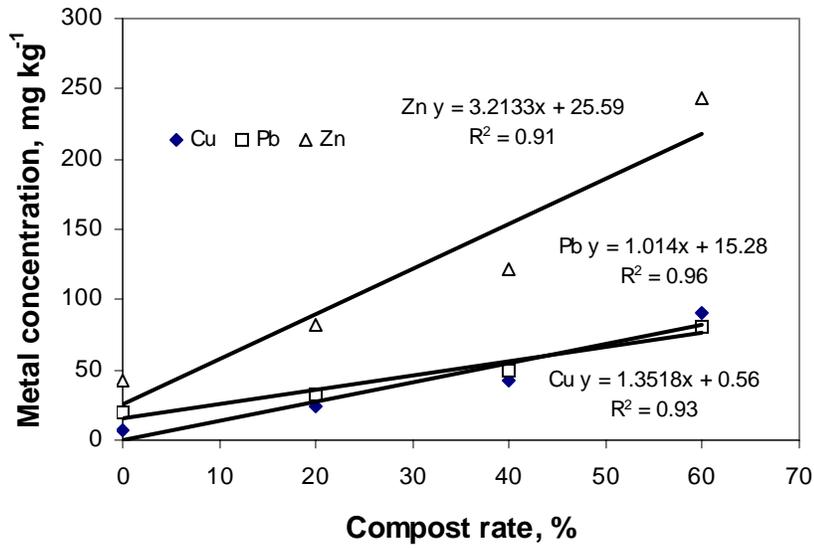


Fig. 8. Influence of the rate of source-separated MSW on soil Cd, Cu, and Pb concentrations (data from Zheljazkov and Warman, 2004)

The increase in total metal accumulation in soil from compost addition also translated into increased labile metal fraction extractable by KNO₃ or DTPA (210, 227). This is illustrated by the data from Wong et al. (227) for Cd, Cu, Ni, Pb and Zn (Fig. 9). Increased accessibility of the metals to plant roots as more MSW compost is added to soil may occur.

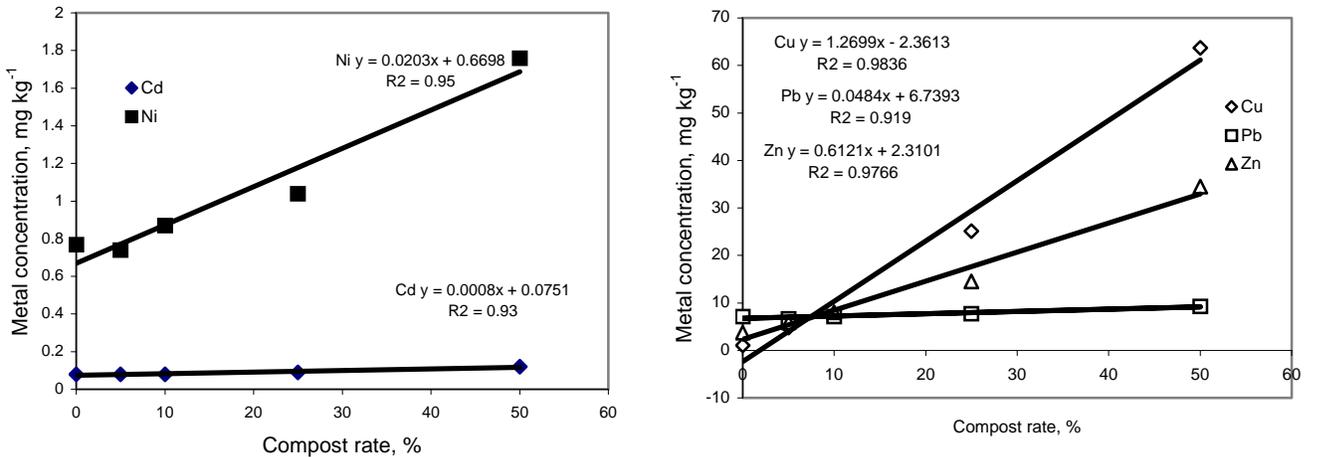


Fig. 9. The influence of compost rate on the concentration of metals extractable by DTPA (227)

As with the organic and inorganic fractions of the compost, soil is long recognized being capable of adsorbing metals to the extent depending on soil texture, pH, organic matter and Fe and Mn oxides content (220). Therefore, compost organic matter and humic acid in particular can alter the availability of soil metal, and soil also can alter the availability of compost metal. The addition of spent mushroom compost and commercial humic acid decreased Zn in the exchangeable fraction, but increased the fractions of Zn associated with organic matter and Mn oxide, thereby redistributing Zn from a more labile to a less labile form (229). This transformation was more evident in the coarse than in the fine textured soil.

Changes in metal fractions after compost has been applied to soil were the subject of a number of investigations (211, 228, 230) with the idea that soil could redistribute compost metal in various fractions. Although the technique used for sequential extractions is not exactly the same among the investigations, the results clearly showed that a trend of the predominance of residual fraction soluble in concentrated HNO₃ for Cd, Cr and Ni, the predominance of Fe and Mn oxide fraction for Pb, Ni, and Zn for some composts, and the predominance of organic matter fraction for Cu. The exchangeable fraction tended to follow the order of Cd > Zn, Ni > Cu, Pb, Cr. Liming tended to shift some organically bound Cu and the exchangeable Zn and Cd toward oxides and residual fractions, which suggests that liming has a particularly influence on the availability of Cd and Zn. The size of each metal in each fraction was also affected to some degrees by the type of composts and by the amount of compost added. The result of sequential extractions affirms the small fraction of compost metals in the readily available form.

The potential of the transfer of added compost metals to plants is a major reason limiting the use of MSW and biosolids composts for crop production. Studies have been done to evaluate the uptake of compost metals by a variety of major and minor crops including wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), oats (*Avena sativa* L.), soybeans (*Glycine max* L.), lettuce (*Lactuca sativa* L.), Swiss chard (*Beta vulgaris* L.), Chinese cabbage (*Brassica chinensis* L.), Swiss chard (*Beta vulgaris* L.), basil (*Ocimum basilicum* L.), among others, under field or greenhouse or growth chamber conditions (211, 216, 223, 226, 227, 230, 231, 232, 233, 234). The diversity of conditions including the compost characteristics and rate, and plant species used in those studies makes it difficult to draw definite conclusions. The studies, however, reveal that in general increasing application rates of MSW or biosolid compost tends to increase plant accumulation of Cd, Cu, Ni, and Zn, but the plant accumulation of Pb and Cr is affected minimally by the composts possibly as a result of their poor translocation from roots to shoots (232).

Whether or not repeated applications of compost at a low rate results in increased availability of compost metal in soil is of concern to the long-term use of metal-contaminated composts in soil. Petruzzelli et al. (210) showed increased metal concentration in corn roots and grain with increasing inputs of metals from MSW compost (Figs. 10, 11, and 12)

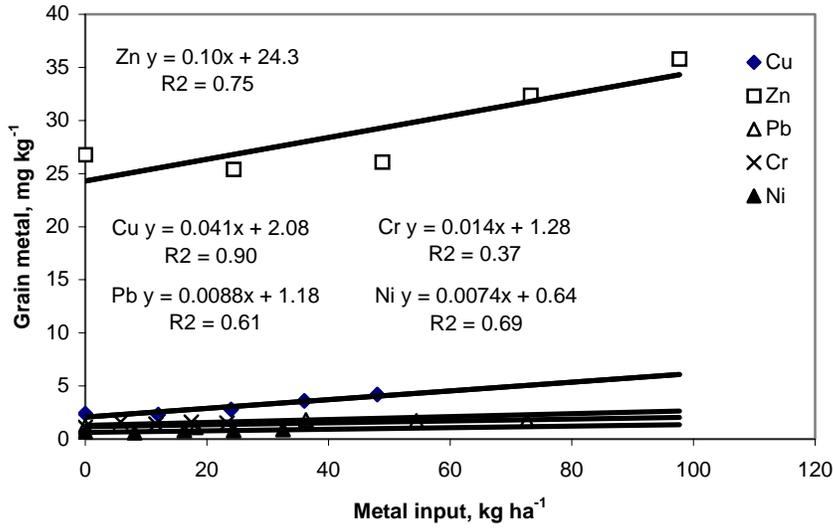


Fig. 10. Accumulation of Cu, Cr, Ni, Pb, and Zn by corn grains from a MSW compost (210)

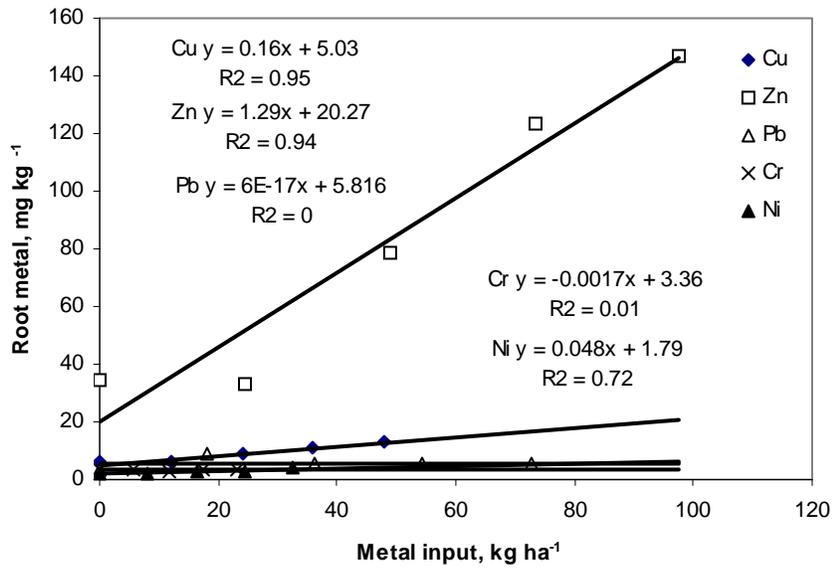


Fig. 11. Accumulation of Cr, Cu, Ni, Pb and Zn by corn roots from a MSW compost (210)

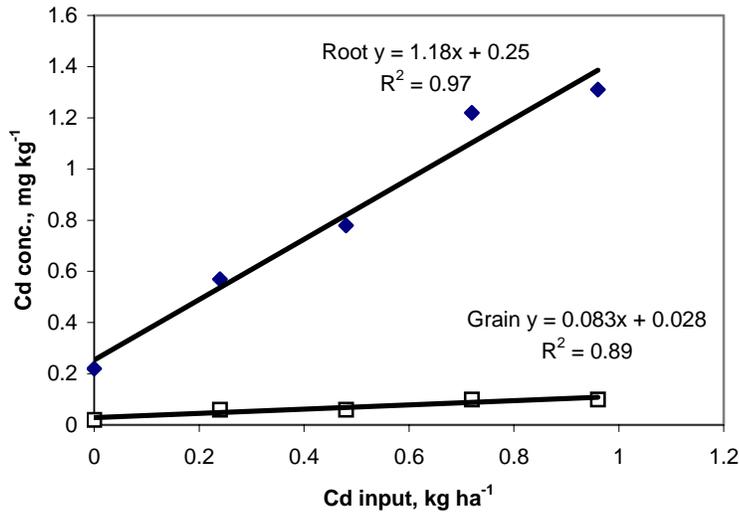


Fig. 12. Cd input from a MSW compost on Cd accumulation in corn roots and grains (210)

The uptake slope of roots was comparatively high for Cd and Zn, intermediate for Cu and lowest for Cr, Pb, and Ni. This was true also for grain. Except for Ni, this order is similar to that for the uptake of the metals by grass and several vegetable crops from biosolid compost (216) averaged across compost rates (Table 22). The uptake slopes for roots and grains for each metal on Figs. 10, 11, and 12 can be converted into transfer coefficients, defined as the ratio of the concentration of the metal in the plant part to the concentration of the metal in the soil (mg kg^{-1}) by multiplying the slopes with a factor of 2.

Table 22. Uptake coefficients for Cu, Cr, Ni, and Zn for several crops (216)

Crop	Cu	Cr	Ni	Zn
Lettuce	0.09	0.042	0.17	0.90
Carrot	0.05	0.028	0.15	0.37
Tomato	0.06	0.016	0.09	0.11
Grass	0.07	0.041	0.20	0.33

The data on Figs. 10, 11, and 12 also emphasize a cumulative effect of compost Cd, Cu, Ni, and Zn addition to the soil on their accumulation by corn roots. A cumulative effect was also found for compost Cd, Cu and Zn, and to a less extent for compost Pb, Cr, and Ni, on their accumulation in corn grains. This indicates that the uptake of particularly Cd, Cu, and Zn by the plant from the compost was not controlled simply by their solubility in the freshly added compost. If this occurred, the past additions of the metals would have little influence on their uptake by the plant and the uptake slope would essentially be zero.

By comparing the metal availability of biosolids before and after compost, Epstein (235) showed composting reduced Cd uptake by corn leave and grain. Composts typically have pH levels near or above neutral (210, 224, 236) and increasing proportions of compost in soil increase soil pH levels (153, 234) at least within a period of time after compost addition. Increased soil pH often decreases accumulation by plants Zn and Cd from a variety of sources (237), and this was true also for compost metal (211). Part of the composting effect on the reduction of Zn and Cd availability to plants has been attributed, at least in part, to soil pH (231). Whether or not simply including soil total metal content along with pH is sufficient to predict metal accumulation in plants across diverse soils remains to be seen. Such a combination was found sufficient to predict Cd accumulation by wheat grain or other crops (238, 239). However, it excludes the role of metal buffering capacity of soil and the organic matter added along with the metals in biosolids or compost. The metal buffering capacity of organics added along with metals is an important factor determining the long-term availability of the added metals (240). For other metals such as Cu, the combination may not work as the increased mobilization of Cu at high pH levels increased, rather than decreased, Cu uptake by plants (211).

Organic matter is one of the important components of soil contributing to its metal retention capability as indicated earlier. Its decomposition in soil over time could lessen soil capability to retain metal and increases metal availability in the soil. This is the basic justification in proposing 'Time Bomb' concept by McBride (241). A rapid increase in flux of CO₂ within the first several weeks after compost had been applied on the forest floor (225) or incorporated in the soil (242) was followed by a very slow degradation rate of 4 to 5x 10⁻⁴ d⁻¹ or lower, if the compost is well mature (243). Since loss of compost C also involves SOC loss via leaching as discussed earlier, a long-term study under the field condition is needed to determine compost C accumulation or depletion rate is. This, in conjunction with field measurement of accumulation of compost metal to plants would allow assessment of the loss of compost C on the compost metal availability in soil. Loss of soil organic C or compost C may not necessarily reduce sorption of compost metal by soil as degradation of SOC increases polymerization of residual C and metal retention capacity. It is likely that the long-term availability of compost metal will be controlled by whether or not metal sorption in the compost amended soil is changed as a result of C degradation (240).

An ability to predict the availability of compost metal, both on the short and long terms, in soil would greatly enhance our ability to manage compost metal in soil. The inclusion of various metal fractions from sequential extractions to predict compost metals accumulation by plants by the multi-regression technique (211) is neither practical nor theoretically sound. Since the addition of organic matter alters metal fractions in soil (229), the degradation of compost C following compost addition to soil could alter metal fractions again. Development of a soil test that reflects the influence of the amount of metal input, soil pH and other soil factors that affect compost metal binding strength and sorption capacity is needed to better predict the availability of compost metal across diverse composts and soil types. This would facilitate the assessment of long-term risk of compost metal accumulation in soil.

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