Chemical and Physical Characteristics of Compost Leachates

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A Review

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Report prepared for the

Washington State Department of Transportation

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Executive Summary

In this paper, we review the existing literature on compost leachates, with special emphasis on the chemical and physical characteristics of the leachate constituents. We briefly summarize the biochemical processes occurring during composting and the use and applications of compost in the environment. We then review the chemical and physical characteristics of feedstock, compost, and compost leachate. We finally discuss environmental implications of the compost leachate.

The compost source material, i.e., the feedstock, determines to a large degree the types of leachates. Well-cured compost has been found to eliminate phytotoxic effects of raw feedstock and promote nutrient availability when applied as soil amendment. Feedstock selection and waste-stream separation play an important role in keeping non-degradable contaminants, like heavy metals and plastics, out of the compost.

Leachate from compost is yellow to dark-brown in color, mainly due to the presence of dissolved and particulate organic matter. Characterization of the amount and type of organic material (both dissolved and particulate) in compost leachate indicates that, in the early stages of composting, the leached organic matter contains oxidized functional groups, and in the later stages of composting, there is an increase of phenolic (a benzene ring with an OH group) functional groups. The increase of phenolic groups indicates degradation of lignin in the maturing compost. Together with the leaching of organic matter, there is evidence for leaching of various nutrients and contaminants present in the original feedstock. Contaminants can leach by direct dissolution out of the compost, as well as with the help of dissolved and particulate organic matter, both of which have a high sorption affinity for inorganic and organic constituents, and which can enhance contaminant leaching via the mechanism of colloid-facilitated transport. Organic matter, nutrient, and contaminant concentrations are highest in the initial leachate, and the concentrations decrease considerably with increasing amount of rain or runoff water leaching through the compost.

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1 Introduction

Most municipal and industrial waste is being disposed off in landfills. However, due to the ever increasing volume of waste, landfill disposal becomes increasingly expensive, and therefore, efforts at minimizing the waste stream are needed. Organic waste can be recycled by composting. Studies at landfills and waste management sites have indicated that more than 50% and potentially up to 75% (by weight) of wastes generated by urban communities and small-scale industrial operations are of organic, and potentially biodegradable nature [*Engineering Solutions and Design, Inc.,* 2004*; Cascadia Consulting Group,* 2009]. Thus, there is great potential for reducing the waste stream through composting.

Efforts to minimize waste streams have led to large-scale recycling of organic waste through composting. The composted end-products are applied to soil to improve both its nutritional and structural characteristics: in farms, public and private gardens, recreational parks, and, on roadsides. Compost is also being used as an amendment in stormwater filtration systems.

While compost has beneficial aspects, such as providing nutrients to plants, increasing soil organic carbon content, and contaminant retention in rain-gardens, the leachate coming out of the compost itself can be environmentally problematic. Proper characterization of the nature of the compost leachate is necessary to predict potential harmful effects of compost applications in the environment. Understanding leachate characteristics also allows optimal design of compost amendments to wetland mitigation sites, rain gardens, bioinfiltration cells, soil treatment layers, bioswales, filter strips, and cartridge and other filter media facilities.

Important questions are how compost interacts with rainfall or runoff water and what the effect of compost leachate is on underlying soil and groundwater. The composition of the leachate from directly applied compost and the change in runoff water quality are questions of special concern.

2 Objectives of this Review

The objective of this paper is to review information on chemical and physical characteristics of compost leachate and highlight environmental implications. Because the leachate is, to a large extent, determined by the raw material (feedstock) and conditions of composting, we first discuss characteristics of feedstock and the compost itself, and then focus on chemical and physical characteristics of the leachate. We then discuss implications of compost leaching on mobilization and retention of nutrients and contaminants.

3 Method of Literature Review

We compiled and reviewed scientific literature on composts and compost leachates with special emphasis on chemical and physical characteristics of the leachate. We surveyed the primary as well as secondary literature using the resources of the Washington State University library system. In addition, we used a number of online resources like those of the websites of the United States Composting Council, various state Department of Transportation, the ScienceDirect database, the American Chemical Society Chemical Abstract Service SciFinder tool (https://scifinder.cas.org), the National Transportation Library

(http://ntlsearch.bts.gov/tris/index.do), and the Transportation Research Board's Research in Progress (http://rip.trb.org). All source documents used in this review were compiled and archived electronically.

4 Basics of Composting

4.1 What is Composting?

Composting is the controlled decomposition of organic material such as leaves, twigs, woodwaste, lawn clipping, food scraps, and other organic matter. Composting involves a wide variety of physical, chemical, and biological transformations of the feedstock. Mesoorganisms, like worms and millipeds, can break down larger aggregates of organic matter mostly by mechanical means. Chemical transformations in the composting process are mediated by microorganisms, primarily bacteria and fungi. The main components of compost are degradation products (e.g., humin, humic, and fulvic acids) of plant and animal body matter (e.g., cellulose, lignin, sugars, and proteins).

4.2 Biochemistry of Composting

The lignin, cellulose, sugars, fats (and waxes), and proteins of the feedstocks constitute the food for the organisms mediating the decomposition during composting Compost feedstocks contain nitrogenous matter aside from the major elemental components of organic compounds (i.e., C, H, and O). The ratio of available C to N is a critical parameter for biodegradation, and optimal composting occurs with a C/N ratio between 20 and 30 [*Rynk et al.,* 1992]. The C/N ratios in most finished compost products are between 12 and 20 [*Rynk et al.,* 1992]. During aerobic decomposition, plant matter like lignin, cellulose, sugars, and proteins become progressively more oxidized to form molecules of lower molecular weight but with more functional groups. The product of this decomposition of organic matter is called humus.

Although biodegradation can occur under both aerobic and anaerobic conditions, composting works best under aerobic conditions. There are microbes that can function without oxygen, but the process of anaerobic respiration is less energy efficient because it uses chemical species like sulfate, sulfur, nitrates, carbon dioxide, oxidized metal ions (like Fe(III), Cr(VI), As(VI), Mn(IV)) as the electron acceptors instead of molecular oxygen. Anaerobic oxidation releases H_2S, NH_3, mercaptans (R–SH), amines (R–NH_2), CH_4, acetates, lactates, and reduced metal ions, products that are undesirable because of their smell or toxic nature. Therefore to prevent anaerobic conditions from developing, artificial aeration is often provided by pushing or pulling air through compost piles.

4.3 Use and Application of Compost

4.3.1 Waste Management

Composting organic waste allows for decomposing the organic materials into a more compact form for management [*Benson and Othman,* 1993*; Tognetti et al.,* 2011]. Compost has been

used at the household or small farm level for recycling of organic matter and nutrients for thousands of years. Since the late 20th century, more and more large-scale composting facilities were established to manage and recycle organic waste from urban areas. Particularly in recent years, these urban composting activities have been viewed as promising efforts to reduce waste streams to landfills and manage waste in a more sustainable manner.

4.3.2 Nutrient Management

Compost is made from a variety of feedstocks such as plants materials from agricultural fields and vegetable gardens, animal waste (manure), municipal solid waste, yard waste (garden and park trimmings), domestic and commercial food waste, and municipal and industrial wastewater processing sludge (biosolids). Green waste is organic wastes primarily consisting of fresh plant material, though domestic and commercial food waste is often included under this classification [*Oregon Department of Environmental Quality*, 2001]. Green waste contains appreciable amounts of nitrogen, phosphorus, and mineral nutrients [*Raj and Antil,* 2011*; Amlinger et al.,* 2003] and has low C/N ratios. Feedstocks such as hay, paper, cardboard, and dry plant leaves contain primarily carbon, oxygen, and hydrogen [*Goyal et al.,* 2005*; Zmora-Nahum et al.,* 2005*; Raj and Antil,* 2011] and have high C/N ratios, such waste is called brown waste. Compost made from green waste usually contains large amounts of nitrogen and phosphorus. Composting therefore plays an important role in nutrient cycling. Currently compost finds use as nutrient sources in farmlands, public and private gardens, parks, highway embankments, and landscaping.

4.3.3 Pathogen Control and Public Health Issues

Pathogen control and degradation of toxic organic compounds by composting are important measures of public health. The composting process is a key method to control pathogenic organisms that are present in municipal sewage and solid waste. Composting involves aerobic respiration by bacterial and fungal organisms, which break down organic matter. The degradation process raises the temperature in the compost piles to between 45°C and 70°C. In this temperature range beneficial thermophilic bacteria thrive, while many bacterial pathogens and weed seeds are killed [*Turner et al.,* 2005*; Erickson et al.,* 2009]. A recent review by *Wichuk et al.* [2011] shows that composting can eliminate most phytopathogens.

Studies have indicated that compost and compost extracts applied to commercially important crops (e.g., wheat, peppers, tomato, okra) can suppress some pathogens and weeds [*Kavroulakis et al.,* 2005*; Tilston et al.,* 2005*; Boulter-Bitzer et al.,* 2006*; Termorshuizen et al.,* 2006*; Yogev et al.,* 2010]. Similar beneficial functions of compost applications have been reported for suppression of snow mold infections of Fusarium Patch and Typhula Blight in turf grass [*Boulter et al.,* 2002]. Composting is also effective in inactivating pathogenic viruses [*Senne et al.,* 1994*; Guardabassi et al.,* 2003*; Bendfeldt et al.,* 2006*; Tablante and Malone,* 2006*; Benson et al.,* 2008*; Guan et al.,* 2010].

4.3.4 Environmental Issues

Oxygen is necessary for bacterial respiration that drives the composting process. Thus, composting occurs best in open-air piles (called wind-rows), or in containers and bins that

have air access. Natural aeration is also often augmented using air pumps. The respiration during the decomposition process in composting causes release of carbon dioxide. Under oxygen-limited conditions, the decomposition process also produces a variety of other gases, like methane, nitrogen oxides, volatile organic compounds, and ammonia. Feedstock high in nitrogen content tends to release considerable amounts of nitrogen oxides and ammonia if anaerobic conditions prevail in the compost pile [*Finstein and Morris,* 1975].

In large composting facilities, rain or snow may fall on compost piles, and the water percolating through the pile can leach out. There is also the possibility of leaching from the feedstock itself. When compost is applied as a soil amendment to agricultural fields, gardens, or roadsides, then soluble and dispersible materials can be leached from the compost by rain or irrigation water. This compost leachate contains soluble minerals, organic matter, and suspended solids, including mineral and organic colloids and potentially pathogens [*Christensen,* 1983*; Christensen,* 1984*; Christensen and Tjell,* 1984*; Boulter-Bitzer et al.,* 2006*; Chen et al.,* 2010]. The exact composition of the leachate is determined by the nature of the feedstock, the degree of progress of the composting process, and the composition of the liquid that infiltrates into the compost. For example, compost applied to roadsides will be exposed to leaching by road runoff, which can carry metals and hydrocarbons. These chemicals will interact with the solid and soluble components in composts, and while some contaminants can become immobilized in the compost, some can leach with compost leachates.

5 Physical, Chemical, and Biological Characteristics

5.1 Feedstock

5.1.1 Categories

The feedstock used is the primary determinant of the composition and physical and chemical properties of the final compost. The feedstock and the manner of composting dictates the essential properties of the compost like the C/N ratio, available macronutrients (e.g., N, P, K, Ca) and micronutrients (e.g., Fe, Mg, Mo) for plant and associated micro flora and fauna (bacteria and fungi). Feedstock and the composting process also influence the structure and texture of the produced compost.

Feedstock for making compost varies tremendously, and depending on its composition, the feedstock and resulting compost may or may not contain contaminants. The types of feedstock also vary seasonally as different materials are available for composting. Feedstock from mixed municipal waste usually contains more contaminants than feedstock that is separated and sorted according to origin, like yard waste, park trimmings, or commercial food waste. Compost feedstocks are regulated in different manner by different jurisdictions, some of which have stringent regulations in separating compost feedstock.

Major classes of organic feedstock suitable for composting are summarized in Table 1, with data from two waste characterization studies carried out in Ohio and California [*Engineering Solutions and Design, Inc.,* 2004*; Cascadia Consulting Group,* 2009]. The table shows that a considerable amount of municipal waste is organic and can be composted. In the California study, for example, it was found that lumber from construction wastes made up around 15% of the total waste stream. Such data indicate the great potential of com-

posting as a recycling method, thereby saving valuable and limited landfill space for more intractable wastes.

5.1.2 Nitrogen Availability and Mobilization

Nitrogen is a macronutrient for plants. Bacterial metabolism can convert organic forms of nitrogen in soil and nitrogen in the atmosphere into inorganic forms of nitrogen (NH_4^+, NO_3^-, NO_2^-) which plants can take up. Mineralized nitrogen is susceptible to loss as dissolved salts in run-off and can cause pollution in surrounding water bodies. *Amlinger et al.* [2003] provides a detailed review of nitrogen availability and mobilization in composts based on biosolid and yard-waste feedstocks.

Himanen and Hänninen [2011] compared different compost feedstocks, i.e., source-separated kitchen waste, anaerobically and aerobically digested municipal wastewater sludge, for their composting activity and nutrient dynamics during the composting process. Table 2 lists C and N contents and C/N ratios for the three composting feedstocks bulked up with sphagnum peat (1:1 v/v). The results show the increasing N-mineralization in the initial stages of the composting process, indicated both by the increased mineralized N content and the decreasing C/N ratio, although the trend is not so clear for the aerobic sludge compost. *Himanen and Hänninen* [2011] also found increased nitrogen losses in form of volatile ammonia, with the aerobic sludge showing as much as 45% nitrogen loss in the initial 8 to 10 weeks. Over the long run though, the nitrogen mineralization rates varied among the feedstocks as reflected by the C/N ratios, with the biowaste compost showing a decreasing C/N ratio and the sludge-based composts showing an increasing C/N ratio.

Guo et al. [2012] investigated the effect of aeration rates, feedstock C/N ratios, and moisture content on a mixed feedstock of pig manure and corn stalks. Compost stability was found to be most dependent on the aeration rates during the composting process. The C/N ratio mainly influenced the maturity (degree of decomposition, humification, and decrease of phytotoxicity) of the compost as indicated by a seed germination index.

Such studies are helpful for predicting nutrient release from compost both from a nutrient management perspective when compost is used as soil amendment as well as from an environmental perspective to understand properties of the compost leachate.

5.2 Compost

5.2.1 Categorization and Characterization

Compost is such a variable and complex material that systematic classification and categorization is difficult. Several researchers have used principles of chemometrics and statistical analysis to classify and characterize compost [*Li et al.,* 2001*; Zbytniewski and Buszewski,* 2005b*; Campitelli and Ceppi,* 2008*; Bustamante et al.,* 2010].

Campitelli and Ceppi [2008] measured 19 parameters of 28 different compost samples differing in feedstocks and processing methods. The authors found a large variation in the parameters, but using statistical methods like principal component analysis and linear discriminant analysis, the most representative indices to categorize composts were found to be total organic carbon, germination index, pH, total nitrogen, and water-soluble carbon.

Table 1: Feedstock classification of compostable wastes. Data from *Engineering Solutions and Design, Inc.* [2004], *Cascadia Consulting Group* [2009], and *Rynk et al.* [1992].

Name	Source	%w/w*	Moisture	Class†	Major constituents††
Paper fibre	Card/paper board, office paper, newsprint, magazines, corrugated paper	35–45	Low	Brown	Cellulose
Yard waste	Green plant matter—domestic and municipal garden and park grass, tree, shrubbery trimmings, roadside leaf litter	8–12	Low or Medium	Green	Lignin, cellulose, sugars—nitrogen, phosphorus, and mineral rich
Food waste	Domestic food waste, commercial food wastes	5–15	High	Green	Sugar, proteins, and fat, some minerals
Forest waste, Lumber‡	Construction, saw-mill dust, wood chips, bark, wood and fiber board industry waste	15‡	Low	Brown	Lignin, cellulose (potentially contaminated with toxic organic compounds and heavy metal from preservatives, paints and fillers)
Sewage sludge (Biosolids)	Municipal sewage and waste water processing sludge/solids	–	Variable	Green	Nitrogen and phosphorus and mineral rich, potentially pathogenic (raw sludge solids), may contain toxic heavy metals
Animal manure	Livestock (mixture of animal fecal matter and bedding materials like straw)	–	Medium or High	Green	Lignin, cellulose, hemicellulose—acidic, nitrogen, phosphorus, and mineral rich, may contain antibiotics
Plant manure	Nitrogenous crops like legumes, seaweeds, brewing industry (spent hops, barley), meat operations (rumen contents)	–	Medium	Green	Lignin, cellulose, hemicellulose, proteins—nitrogen and phosphorus rich
Farm waste (Non-manure)	Hay, straws, chaff	–	Variable, usually Low	Green	Usually high C/N ratio, mineral rich
Biomedical wastes	Hospitals, hospices, clinics	<3	Low	§	Usually polymers, glass and metal, contaminated with body fluids, potentially pathogenic unless source segregated
Other	Diapers, textiles (clothes, upholstery, drapery)	<10	Low or Medium	Brown	Mostly cellulose, may contain nitrogen from synthetic fibers, some potentially polymeric material hard to degrade in compost

* Percentage of the total incoming waste at 11 municipal solid waste centers in Ohio [*Engineering Solutions and Design, Inc.,* 2004], unless noted otherwise. † Green wastes are typically fresh plant material and have low C/N ratios of 10–20, brown wastes are usually more carbonaceous (C/N ratio > 35). †† "Mineral rich" means a substantial amount of ash content when incinerated; most ash contains silica and salts of alkali/alkali earth metals (Na, K, Ca, Mg being the most common), sometimes also Ca and Fe phosphates. ‡ Values from the California Waste Characterization Study [*Cascadia Consulting Group,* 2009]. § Many constituents are non-degradable during composting.

Table 2: Characteristics of feedstocks (raw) and composts at different maturity levels (after week 1, 8, and 63). Adapted from *Himanen and Hänninen* [2011].

		1:1 v/v sphagnum peat		
Characteristic	Age	+ Kitchen Bio-waste	+ Aerobic Sludge	+ Anaerobic Sludge
Dry matter (%)	Raw	31.4±0.0	15.4±0.0	16.0±0.0
Ash (%)	Raw	23.0±3.3	19.2±1.6	19.6±0.2
LWCA water (g/kg)	Raw	8.6±0.7	13.8±0.8	11.2±0.6
LWCA NaOH (g/kg)	Raw	12.3±0.7	14.3±1.0	6.6±4.6
Total C (%)	Raw	39.0±0.6	36.5±0.4	34.1±0.6
	Week 1	39.0±0.6	36.5±0.4	34.1±0.6
	Week 8	33.1±1.5	34.1±0.6	31.4±0.2
	Week 63	33.4±1.3	34.2±0.4	28.1±0.9
Total N (%)	Raw	2.0±0.1	2.4±0.02	2.1±0.03
	Week 1	2.0±0.1	2.4±0.02	2.1±0.03
	Week 8	2.5±0.1	2.3±0.03	2.4±0.04
	Week 63	2.6±0.1	1.7±0.10	1.7±0.04
C/N ratio	Raw	20	15	15
	Week 1	20	15	16
	Week 8	13	15	13
	Week 63	13	20	16
Inorganic N (% Total N)	Week 1	4.5	10.8	9.5
	Week 8	17.1	25.7	29.7
	Week 63	16.6	23.5	6.9
N loss (% N at week 1)	Week 8	8.7	45.2	1.4
	Week 63	5.3	41.4	38.8

Note 1: All mean and ±SD were of 3 replicate subsamples (except the LWCA (low-weight carboxylic acids) which were of 4 replicate sub-samples). **Note 2:** All values (except % dry matter, C/N ratios and inorganic N) are expressed as % of dry weight or per kg of dry weight.

Zbytniewski and Buszewski [2005b] categorized sewage sludge compost into three distinct stages of maturity based on the duration of composting: ≈1 week, 3–4 weeks, and 6–8 weeks.

Advanced analytical separation and quantitation techniques, such as size-exclusion, gas and gel chromatography, mass spectrometry, NMR-, FT-IR- and ICP-AES spectroscopy, and isotopic tracer studies, are being increasingly used to characterize the composting process and its end-products [*Wershaw et al.,* 1996*; Zbytniewski and Buszewski,* 2005a*; Zbytniewski and Buszewski,* 2005b*; Tang et al.,* 2006*; Noble et al.,* 2009*; Soriano-Disla et al.,* 2010*; Iwai et al.,* 2013]. Application of such techniques helps identify and quantify the chemical nature of compost products.

5.2.2 Physical and Chemical Properties

Dresbøll and Thorup-Kristensen [2005] investigated the physical properties of produced compost and the process parameters of composting based on plant residue feedstock from three

Table 3: Average values of chemical properties of composts grouped by primary source material. Adapted from *Zmora-Nahum et al.* [2007].

Property	Oilcake	Grape marc	Manure	SMS†	Wood	Green
pH	6.3	6.8^{a}	8.0^{a}	7.0^{a}	7.7^{a}	8.0^{a}
OM† (%)	73.9	76.	46.5^{a}	45.6^{a}	24.0^{b}	36.1^{ab}
Organic C (%)	40.9	42.2	25.5^{a}	25.6^{a}	12.8^{b}	20.3^{ab}
N (%)	3.0	2.7^{a}	1.9^{ab}	2.1^{ab}	0.9^{c}	1.1^{bc}
C/N	14.3	15.	13.5	13.2	14.5	18.9
DOC† (mg/L)	2920	1470^{a}	1050^{a}	115^{a}	240^{a}	400^{a}
EC† (dS/m)	5.3	3.0^{ab}	4.1^{a}	3.4^{ab}	1.3^{b}	1.3^{ab}
N-NO_3 (mg/L)	23.9^{a}	63.6^{a}	146.1	17.7^{a}	23.6^{a}	14.5^{a}
Sugars (mg/L)	1004	662^{a}	260^{a}	629^{a}	172^{a}	180^{a}

† OM = Organic Matter, SMS = Spent Mushroom Substrate, DOC = Dissolved Organic Carbon, EC = Electrical Conductivity. $^{a-c}$ For each property, values with a different letter are significantly different ($p < 0.05$).

different species of plants (wheat, hemp, and miscanthus). The authors indicated that different plant feedstocks changed the texture of the compost produced noticeably, affecting parameters like water retention, particle size distribution, C/N ratio, and the amount of mineralized nitrogen.

Physical and chemical properties of commercial compost based on their feedstocks and location of origin were investigated by *Zmora-Nahum et al.* [2007]. The authors found that while the compost properties differed widely, there was significant correlation of properties based on the type feedstock (Table 3). The authors also found that the compost properties had more uniformity when the source of the compost was from a country which had tighter regulations of compost feedstocks, e.g., the properties of composts from the Netherlands, where waste streams going into composting are strictly regulated, were more uniform than in France and Greece, where the regulations are less stringent. The chemical properties of compost were also found to correlate well with the feedstock type, e.g., feedstocks containing recalcitrant wastes like oil-cake or grape marc composted slowly compared to those containing easily compostable green waste (fresh plant matter, like lawn and park trimmings, kitchen and garden waste) or woody waste (lumber, bark, sawdust).

5.2.3 Microbiology

Microbes are major drivers of the composting process, and as such, characterization and identification of microorganisms in compost is important to better understand degradation mechanisms. Microbial community structures change during the composting process as temperature and chemical conditions change. *Blanc et al.* [1999] classified the microbial variety in composts using a combination of population counts and rDNA isolate tests. The authors reported that thermophilic bacteria were being replaced with less thermophilic bacteria as the temperature in the compost pile dropped below optimal ranges for thermophilic bacteria [*Blanc et al.,* 1999]. Their results indicate that as temperature declines and the chemical

composition of the compost materials becomes more diverse, the compost is populated with a broader rage of microorganisms. While the conditions during compositing are generally aerobic, there exist anaerobic sites in micro-environments [*Blanc et al.,* 1999]. Such microsites can harbor strictly anaerobic, thermophilic bacteria [*Vancanneyt et al.,* 1987]. Microbial populations in compost depend upon feedstock and composting methods [*Dees and Ghiorse,* 2001].

Avery et al. [2012] investigated the ability of pathogenic microbes to enter source-separated green wastes and their survival during the composting process. Common pathogens, e.g., *Escherichia coli*, *Salmonella* spp., *Campylobacter* spp., and *Giardia* spp., were found to be destroyed or inactivated during composting over periods of 1 to 16 weeks. However, the authors also found classes of pathogens which were resistant to inactivation by the composting process, e.g., spore-forming bacteria like *Clostridium* spp. and *Bacillus* spp., the bacterium *Legionella longbeachae*, and fungi like *Aspergillus fumigatus*. The authors highlighted the need for more in-depth studies of prevalence of pathogens in compost feedstock as well as in the target environment where such composts are usually applied (e.g., agricultural, park, and garden soils).

5.2.4 Maturity and Stability

The chemical and physical stability of the compost determines the shelf-life and applicability of compost for various uses. A stable compost is one that shows an advanced degree of organic matter decomposition with resistance to further decomposition [*Mondini et al.,* 2003*; Wichuk and McCartney,* 2010]. A stable compost shows steady values of a number of indices like respiration rates [*Wu et al.,* 2000], microbial count and biomass, organic matter content, C/N ratio, and storage temperature [*Baffi et al.,* 2007*; Wichuk and McCartney,* 2010]. A related term that is also used, sometimes interchangeably, is the maturity of compost.

Many authors consider compost maturity from the viewpoint of how beneficial the compost is to plants, as determined by indicators like germination rates, plant growth (biomass formation) assays, and residual content of phytotoxic compounds, like pesticides and low-molecular weight organic acids [*Iannotti et al.,* 1993*; Wu et al.,* 2000]. For example, measurement of microbial respiration and oxygen uptake rates are often used to monitor the composting process and assess compost maturity [*Lasaridi and Stentiford,* 1998*; Wu et al.,* 2000*; Borken et al.,* 2002*; Boulter-Bitzer et al.,* 2006*; Scaglia et al.,* 2007*; Kalamdhad et al.,* 2008*; Tejada et al.,* 2009*; Soriano-Disla et al.,* 2010*; Komilis and Kanellos,* 2012].

Maturity and stability of compost can also be assessed by determining changes in chemical structure of the compost over time. *Tang et al.* [2006] used solid-state ^{13}C NMR, respiratory quinone profiles (amount of quinone enzymes), elemental composition, and germination indices to determine changes in compost characteristics during the maturing period (up to 18 months). The results indicate that the initial microbial biomass that had developed during the thermophilic stage was maintained for 2 to 4 months, but then a decrease in carbon content, C/N ratio, microbial biomass, microbial variety, and phytotoxicity was observed.

Common indicators of compost maturity and stability are germination rates (phytotoxicity) and amounts of soluble organic matter (humic and fulvic acids), which indicate degree of humification. *Bustamante et al.* [2010] used the germination index (percentage of germinating seeds in a compost sample of a given age compared to a control growth medium) and

the amount of dissolved organic matter from compost extracts to assess compost maturity.

Sayara et al. [2010] investigated the ability of composts with different stability (as denoted by respiration rates and percent organic matter) in remediating a soil sample intentionally contaminated with mixtures of polyaromatic hydrocarbons (PAHs). The results indicated that stable composts degraded as much as 98% of the PAHs after 30 days, whereas the most unstable (poorly composted) sample achieved only 40% degradation of PAHs. Detailed reviews on assessment of compost maturity using different techniques are discussed in *Woodbury and Breslin* [1992], *Bernal et al.* [2009], and *Kumar* [2011].

5.2.5 Phytotoxicity

Many phytotoxins, which are compounds detrimental to plant growth, come from agricultural use of pesticides, industrial solvents, propellants, and refrigerants (e.g., halogenated alkanes, alkenes, and aromatic (aryl) hydrocarbons), degradation of waste plastics (polymers, pigments, bulking agents, and filler materials), and stormwater runoff.

Composting facilitates microbial degradation of organic molecules with phytotoxic properties, and in addition, organic matter generated through composting can bind phytotoxic metals and thereby reduce their bioavailability. Direct germination rates, or a modified germination index (comparison of germination rates of a test vs a control growth media) have been used as indicators of phytotoxicity in composts [*Pascual et al.,* 1997*; Tiquia et al.,* 1997*; Tiquia and Tam,* 1998*; Tiquia and Tam,* 2000*; Wu et al.,* 2000*; Tang et al.,* 2006*; Campitelli and Ceppi,* 2008*; Himanen and Hänninen,* 2011]. For example, *Himanen and Hänninen* [2011] investigated compost maturity by measuring the phytoxicity via germination rates. Phytotoxicity levels almost reached zero after eight weeks of composting in three different feedstocks (kitchen biowaste, aerobic and anaerobic waste water sludge).

5.2.6 Organic Matter, C/N Ratio, and Nutrients

Figures 1–3 show major chemical structures of organic compounds and moieties commonly found in compost feedstock and in organic matter extracted from soil and compost. The method of extraction of the major soil (or compost) organic matter fractions—humin, humic acids, and fulvic acids—are described in soil chemistry textbooks (e.g., *Hayes and Swift,* 1978, *McBride,* 1994, *Stevenson,* 1994, *Sposito,* 2008).

Nutrient and organic matter contents of composts have been studied extensively [*Goyal et al.,* 2005*; Zmora-Nahum et al.,* 2005*; Hernández et al.,* 2006]. The ratio of the carbon to nitrogen (percent of dry weight) is a key indicator of the compost's suitability as a growth medium. For example, 40% C content, 2% N content has a C/N ratio of 20, which is on the upper range of C/N ratio for a good compost [*CalRecycle,* 2006]. Ideal C/N ratios for a compost used as a growth medium is 12–18 [*CalRecycle,* 2006].

The C/N ratio is an important indicator for the fate of N during microbial mineralization [*Golueke and McGauhey,* 1953*; Raabe,* 2001*; CalRecycle,* 2006]. *Iglesias-Jiménez* [2001], for example, studied actual nitrogen availability from mature composts applied to a standard soil sample spiked with ^{15}N using the $^{15}N/^{14}N$ isotope dilution method. The authors indicate that compost matured over three months made from mixed city waste feedstock, which is usually considered a poor nitrogen releasing feedstock, shows good nitrogen release to plants.

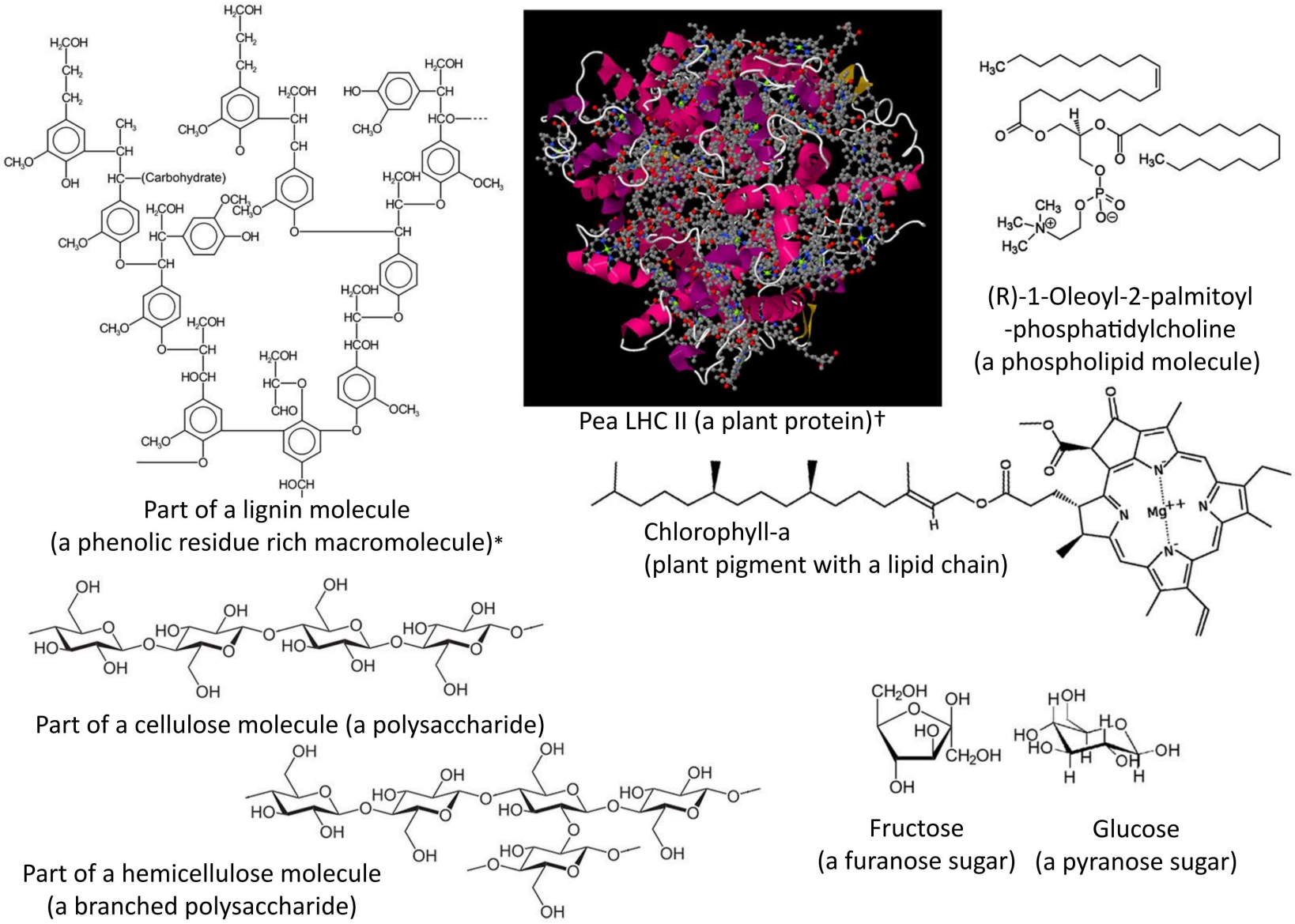

Figure 1: Chemical structures of organic moieties/molecules found in feedstock. (*Structure adapted from *Sakakibara* [1983], †Structure visualized using JMol PDB viewer using Protein Data Bank file 2BHW)

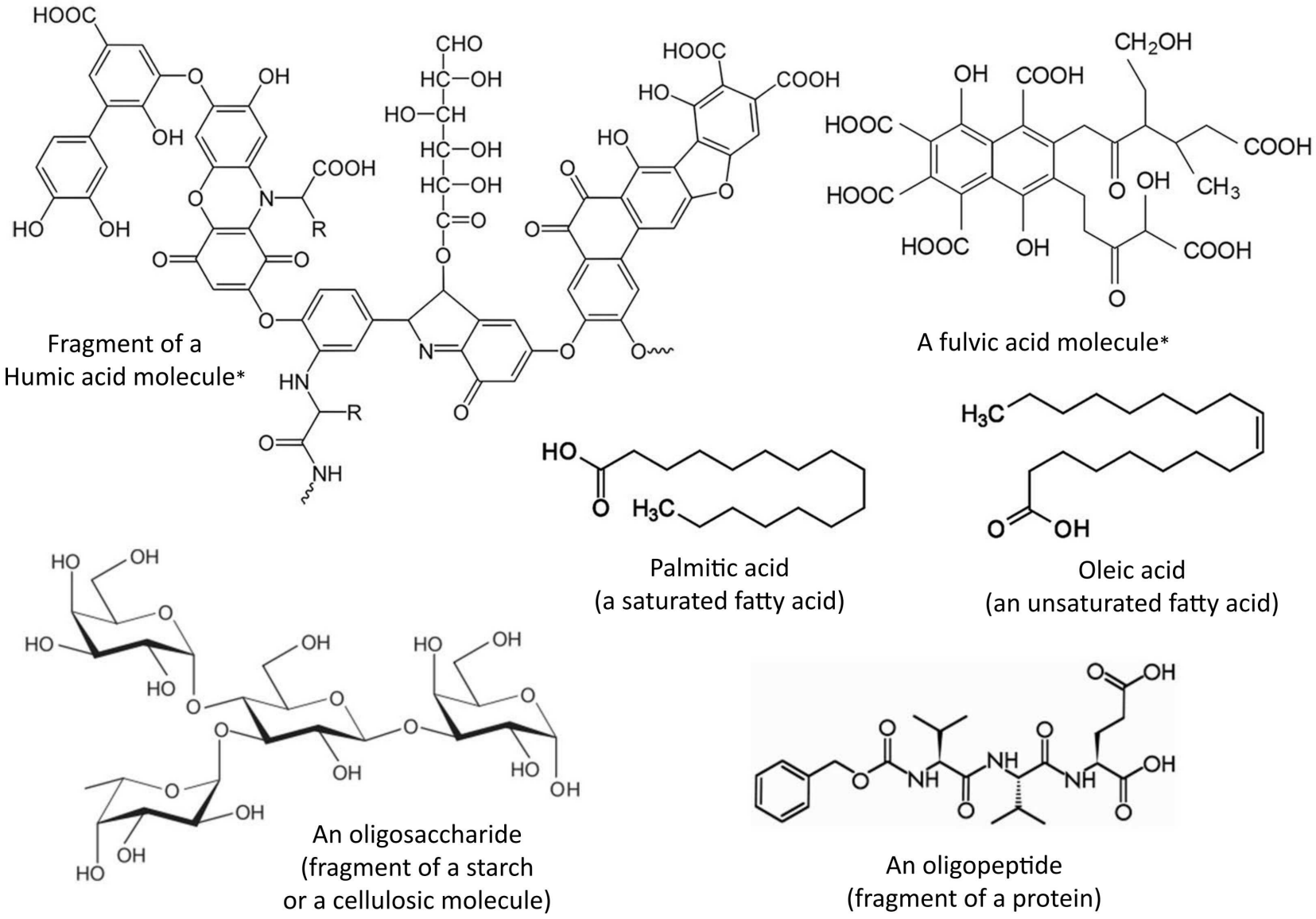

Figure 2: Chemical structures of organic moieties/molecules found in mature compost. *Structures adapted from *Stevenson* [1994]

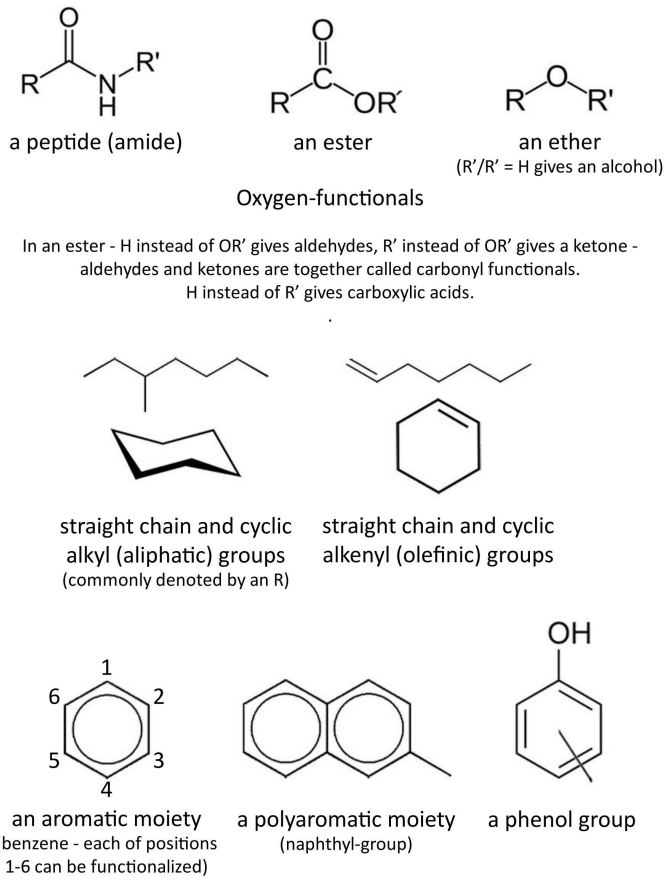

Figure 3: Common functional groups/moieties in organic matter found in mature compost.

Doublet et al. [2010] investigated the variation in the C/N ratio and extent of nitrogen mineralization in different particle size fractions in sludge-based compost. The C/N ratio of the 0–50 μm particle fraction was an indicator of degree of sludge transformation and humification. The larger particle size fractions continued degrading organic matter and mineralizing nitrogen even after 13 weeks, indicating the importance of particle size in the composting process. *Kumar* [2011] provides a review of C/N ratios of compost derived from a variety of feedstocks.

Zmora-Nahum et al. [2005] found that dissolved organic carbon (DOC) is a consistent indicator of compost maturity across several different feedstocks and processing methods. The authors recommend a value of 4 g DOC/kg-compost as an indicator of a mature compost, irrespective of the compost feedstock or the composting methodology. The measurement of DOC itself is suggested by UV/Visible absorbance at 465 nm.

The humic material content is a good indicator of the quality of the compost produced and its efficacy in nutrient management, especially as a soil amendment to improve water retention and fertility. There exists a large number of studies on characterization of humic materials from composts [*Christensen and Nielsen*, 1983*; Inbar et al.*, 1990*; Ciavatta et al.*, 1993*; Prudent et al.*, 1995*; Davies et al.*, 2001*; Campitelli et al.*, 2006*; Spaccini and Piccolo*, 2009]. *Spaccini and Piccolo* [2009] investigated the molecular characteristics of humic sub-

stances extracted from composts at increasing stages of maturity. The results obtained from NMR spectra and thermochemolysis show increasing uniformity in properties of the humic substances with increasing composting time. The constituents of the stable fraction of humic substances were found to be linear and cyclic lipids, phyto-polysaccharides and aromatic compounds. Progressive maturity of the compost was characterized by the presence of more O-alkyl (ester and ether, Figure 3) carbon. Increasing compost stability was also indicated by preservation of hydrophobic (non-polar) moieties and incorporation of labile, nitrogenous functionalities like peptide (Figures 1 and 3) fragments. The hydrophobic components in humic acids also contributed to better retention of nutrients and contaminants [*Spaccini and Piccolo,* 2009]. Composts with high humic acid content are useful soil amendments, especially to increase and sequester soil carbon [*Fortuna et al.,* 2003], to remediate contaminated soils [*Conte et al.,* 2005], and to control nutrient runoff [*Tsui et al.,* 2007].

5.2.7 Heavy Metals

Heavy metal concentrations in composts (usually produced from mixed waste and industrial waste streams) have been extensively investigated [*Christensen and Tjell,* 1984*; Fuentes et al.,* 2006*; Cai et al.,* 2007*; Paradelo-Núñez et al.,* 2007*; Gao et al.,* 2008*; Chen et al.,* 2010*; Hartley et al.,* 2010*; Helmreich et al.,* 2010*; Andersen et al.,* 2011*; Himanen and Hänninen,* 2011] primarily because of their toxic effects on organisms and potential for long-term accumulation in the food-chain.

Toxicity is related to the physiological availability of the metals and depends on the target organism. Bioavailability of heavy metals can change with the type and maturity of the compost [*Moreno et al.,* 1996*; Guerra-Rodríguez et al.,* 2006*; Cai et al.,* 2007*; Ingelmo et al.,* 2012]. *Ingelmo et al.* [2012] studied bioavailability of heavy metals (Zn, Pb, Cu, Ni, and Cd) in a relatively low stability compost (C/N ratio of 22 and composted for 20 weeks) made from primarily carbonaceous feedstocks (sewage sludge and wood chips, C/N ratio of 30). The authors assessed bioavailability by measuring metal concentrations in different extracts: metals extracted by water, 0.5 M KNO_3, 0.5 M NaOH, and 0.05 M EDTA (ethylene diamine tetraacetic acid) were considered to have medium-level bioavailability, metals extracted by 4 M HNO_3 were considered to have low-level bioavailability. Results indicate that metal ions (except Pb) become more bioavailable in the compost than in the original feedstock.

If humans or other mammals accidentally ingest compost material, heavy metals may become more bioavailable than in aqueous solutions typical for environmental conditions. This availability to mammals can be assessed with a class of standardized tests known as the Physiologically Based Extraction Tests where metals are extracted with a standard solution (of pepsin, citric, acetic, and malic acids buffered to pH 2) [*Miller et al.,* 1981*; Crews et al.,* 1983*; Ruby et al.,* 1993*; Hack and Selenka,* 1996]. This solution extracts more metals than just plain water, suggesting the higher bioavailability of toxic metal ions under physiological conditions [*Miller et al.,* 1981*; Ruby et al.,* 1993]. *Paradelo-Núñez et al.* [2007] used such a test to study the physiological availability of Cu, Zn, Cd, Cr, Ni, and Pb from four different composts.

Removal of Cd, Cu, and Zn from synthetic stormwater by using columns of sand amended with various levels of compost was studied to determine the metal retention capacity of bioretention systems [*Morgan et al.,* 2011]. Breakthrough curves for the metal ions

were recorded and sorption models were used to predict removal efficiency as well as life span of the bioretention systems. The results showed that for a 70% sand and 30% compost mix, a 90% reduction in metals in the outflow was achieved and the lifespan of the bioretention systems was found to be 95 years. However, it was found that phosphorus release occurred from the bioretention media in considerable amounts, unless initial phosphorus contents in the compost were low.

5.2.8 Chelation and Multi-Site Sorption

The composting process consists of decomposition of biological polymers and complex molecules. The end product of the process is a class of poorly classified, highly variable organic matter called humus. Humus consists of partly decomposed organic materials and newly formed humic and fulvic acids. Humic and fulvic acids contain a large number of functional groups, and particularly humic acids have both hydrophobic and hydrophilic properties (Figure 2). This ambiphilic characteristics of humic substances makes them ideal adsorbents for both hydrophobic organic molecules, like pesticides and polyaromatic hydrocarbons (PAHs), and hydrophilic polar organic molecules and heavy metals.

5.2.9 Organic Pollutants

Most modern pesticides (insecticides, fungicides, herbicides) are organic compounds, which can be decomposed by biological metabolic processes. However, organic compounds adsorbed onto organic matter, are often less available for microbial degradation. This is the reason why pesticides applied to soils can persist for a long time. For example, *Cogger et al.* [1998b] found that simazine, a common, triazine herbicide used for broad-leaf weed and annual grass control, persisted in soils for up to four years, with a disappearance half-life of four to six months. Results from similar experiments with carbofuran, a carbamate insecticide, showed that carbofuran degrades quicker in soil than simazine, but the enhanced degradation was only associated with freshly applied insecticide not with the residuals left over from previous applications, which appeared to be more recalcitrant and less labile [*Cogger et al.,* 1998a]. Though such studies were conducted in soils, but organic matter from compost applied to the environment is expected to have similar effects.

A few reviews have dealt with pesticide degradation in compost [*Buyuksonmez et al.,* 1999*; Buyuksonmez et al.,* 2000*; Barker and Bryson,* 2002]. *Buyuksonmez et al.* [2000] concluded that pesticides in composting feedstock are not a major cause for concern because the pesticides are decomposed during the composting process. However, some recalcitrant pesticides, notably organochlorine compounds, continue to be of concern. These organochlorines tend to remain adsorbed on complex organic matrices thus becoming unavailable to microbial degradation. Notable examples of such compounds are chlordane, dieldrin, and DDT (or its de-hydrochlorination product, DDE). Even though organochlorine compounds in soils have been found to degrade during the composting process to about 15% of their initial values, the remaining amount was found to be environmentally non-degradable [*Valo and Salkinoja-Salonen,* 1986].

Organic pollutants, like organophosphate and carbamate pesticides, are degraded effectively and found in low concentrations in composts. However, the reduction of concentrations

and the mechanism of degradation vary with the particular pesticide and the parameters of the composting process. Also, due to inadequate data on degradation levels and pathways it is difficult to make predictions on what the effect of composting may have on a particular pesticide [*Buyuksonmez et al.,* 2000].

5.3 Leachate

5.3.1 What is Compost Leachate?

Compost leachate is the liquid coming out of compost when water from irrigation, precipitation (rain or snow), or runoff seeps through the compost. The chemical and physical nature of the compost leachate is of key importance as the leachate migrates into underlying soils and groundwater, or flows as runoff into surface water bodies. Compost leachate carries both dissolved species and particulate materials suspended in the liquid, such as colloids and larger particles. Suspended organic and inorganic materials in the form of colloids have been implicated in the mobilization of organic contaminants and inorganic, toxic heavy metal ions [*McCarthy and Zachara,* 1989].

Initial leachate out of active compost piles or fresh compost are often yellowish, pale-brown or dark-brown in color due to the dissolved and particulate organic matter [*Callaghan,* 2012*; CalRecycle,* 2012]. Compost leachate is also rich in soluble nutrients [*Callaghan,* 2012*; CalRecycle,* 2012]. Compost leachate is similar to compost extracts, the latter are made by intentionally soaking compost (active or mature) in excess water to sample the soluble matter in the compost, whereas the former is the result of drainage of excess water carrying soluble and particulate matter. Compost tea, on the other hand, is different in that it is produced by active brewing of compost with microbial nutrients and catalysts [*CalRecycle,* 2012].

5.3.2 Dissolved and Colloidal Organic Matter

The composting process converts some of the original organic matter into humin, humic acids, and fulvic acids. These constituents can be present in compost leachate in both dissolved and particulate (i.e., colloidal) form. The exact chemical structure of dissolved and colloidal organic matter differs depending on feedstock type and composting conditions and age. Humic and fulvic acids are not single molecules, but rather made of assemblies of smaller molecules, typically less than 2000 Da in molecular weight, which are held together by hydrogen bonding and hydrophobic interactions [*Piccolo,* 2001*; Piccolo,* 2002*; Sposito,* 2008]. These assemblies are known as supramolecular associations [*Piccolo,* 2001*; Piccolo,* 2002]. Typical chemical structures of components humic and fulvic acids are shown in Figure 2.

Said-Pullicino et al. [2007] monitored the progress of the composting process over 250 days by studying the water extractable organic matter (WEOM) at different times. The study involved monitoring the composting of a mixed feedstock (w/w, 55% source separated municipal solid waste, 30% yard waste and 15% foliage residue from tobacco cultivation). The WEOM was characterized using UV absorbance at 254 nm at dilution levels of < 10 mg-C/L which was then compared with standard spectra of aromatic organic compounds. The WEOM was fractioned into hydrophobic and hydrophilic parts based on XAD-8 resin separation. The fractionated WEOM was characterized by liquid state ^{1}H and ^{13}C-NMR.

Table 4: Organic matter evolution in water extractable organic matter (WEOM) during composting. Table adapted from *Said-Pullicino et al.* [2007].

	Hydrophilic fraction				**Hydrophobic fraction**			
	^{1}H-NMR Signal Intensities (%)							
Day	olefinic/ aromatic	oxygen-functional	aliphatic		olefinic/ aromatic	oxygen-functional	aliphatic	
0	5	17	78		11	18	70	
13	3	18	79		12	17	70	
28	3	25	72		11	12	77	
250	13	32	55		13	18	69	
	^{13}C-NMR Signal Intensities (%)							
Day	carboxyl/ carbonyl	aromatic	O-alkyl	alkyl	carboxyl/ carbonyl	aromatic	O-alkyl	alkyl
0	25	10	28	37	13	23	26	38
13	27	4	35	33	16	22	23	38
28	27	3	39	31	17	24	17	42
250	23	21	29	27	18	7	6	69

See Figure 3 for chemical structure of these moieties.

Phenolic content in WEOM (usually from lignin degradation) was also measured chemically by oxidizing the WEOM with alkaline CuO followed by a solid-phase extraction.

The ^{1}H-NMR results in Table 4 indicate increasing oxygen functionalization in the hydrophilic fraction at the expense of aliphatic (straight-chain) moieties, suggesting microbial oxidation and uptake of carbohydrates. The trends for the ^{1}H-NMR in the hydrophobic fractions were not so conclusive; however, the trends in the ^{13}C-NMR in the hydrophobic fraction show a relative increase in phenolic compound content at the expense of O-alkyl character, indicating microbial degradation of carbohydrates and an increasing content of lignin-degradation products. There are also trends of increasing alkyl carbons suggesting chain length heterogeneity and an increase of carboxyl carbons suggesting high oxidation in the WEOM [*Said-Pullicino et al.*, 2007].

UV-Vis and ^{13}C-NMR spectroscopy was used by *Zbytniewski and Buszewski* [2005a] to investigate the distribution of carbon functionalities in progressively maturing compost from sewage sludge feedstock. The NMR analysis showed an abundance of methoxyl-groups, typical of freshly formed humic acids. A comparison of fresh compost humic acids with standard humic acid shows the increasing attachment of oxygenated functional groups (especially carboxyl groups) to aromatic moieties rather than to aliphatic chains. The rise in phenolic moiety indicates the progressive degradation of lignin after an initial drop, when the available phenolic moieties are used up by microbial processes.

UV-Vis absorbance was used to determine the degree of humification in the actively composting material by using compost extracts [*Zbytniewski and Buszewski*, 2005a]. The compost extracts were prepared by mixing 1 g compost and 50 mL 0.5 molar NaOH, shaken

for 2 h, then kept overnight, and finally centrifuged at 3000 rpm for 25 min. Absorbance (A) of the supernatant from compost extracts was measured at various stages of the composting at $\lambda = 280$ nm (A_{280}, non-decomposed lignin and quinine moieties), 472 nm (A_{472}, organic matter in the initial actively decomposing stage), and 664 nm (A_{664}, organic material with high content of aromatic and condensed functional groups—denoting stable humified material). Absorbance ratios, indicating the degree of humification, were calculated as follows [*Zbytniewski and Buszewski,* 2005a]:

$$Q_{2/4} = A_{280}/A_{472} \qquad Q_{2/6} = A_{280}/A_{664} \qquad Q_{4/6} = A_{472}/A_{664} \tag{1}$$

The $Q_{2/4}$ reflects the progress of the composting process. The $Q_{2/6}$ denotes the degree of conversion of feedstock materials to final humified material, and is thus an indicator of compost maturity. The $Q_{4/6}$, often called the 'humification index', is an indicator of the stability of the compost because it denotes the ratio between actively degrading and fully degraded material.

Typical values of the $Q_{4/6}$ ratio for soil humified material are less than 5. However, *Zbytniewski and Buszewski* [2005a] found that the $Q_{4/6}$ values stabilized at 8.8 after 53 days of composting. The authors inferred that either the $Q_{4/6}$ values of compost humic substances are different from those in soils or that the composting was incomplete.

5.3.3 Interactions of Organic Contaminants with Dissolved and Colloidal Organic Matter

Organic contaminants strongly interact with dissolved and colloidal organic matter. *Chiou et al.* [1986], using a test set of organic pollutants and pesticides (p,p'-DDT, 2,4,5,2',5'-PCB, 2,4,4'-PCB, 1,2,3-trichlorobenzene, and lindane), showed enhanced solubility of the chemicals in solutions containing dissolved organic matter (DOM). The apparent solubility (S_w^*) of the pollutants/pesticides were related to the actual water solubility (S_w) as [*Chiou et al.,* 1986]:

$$S_w^* = S_w(1 + XK_{DOM}) \tag{2}$$

where X is the amount of dissolved or particulate DOM per mL of water and K_{DOM} is the partition coefficient of the pollutant or pesticide between pure water and DOM. Tests were carried out with different amounts of standard samples of DOM like humic acids, fulvic acids, and humin. Comparative measurements were also made with low (phenylacetic acid) and high (poly-acrylic acid) molecular weight organic co-solutes. The results indicate a linear correlation between the DOM concentration in water and the enhancement of pollutant or pesticide dissolution and mobilization. The greatest extent of enhanced dissolution was provided with humic acids, and DDT was the most sensitive to DOM in water. The results also demonstrate that the pollutants or pesticides were having a partition-like interaction with the DOM in water as evidenced by the much reduced extent of such effects with co-solutes like phenylacetic acid or poly-acrylic acid, which do not provide the required non-polar local environments for pronounced partition effects.

There is evidence that DOM can mobilize organic pollutants from contaminated compost and other waste materials [*Aggelides and Londra,* 2000*; Hartlieb et al.,* 2001*; de Guardia et al.,* 2002*; Bolea et al.,* 2006*; Said-Pullicino et al.,* 2007]. *Hartlieb et al.* [2001] used ^{14}C

Table 5: Partitioning of Benzo[k]fluoranthene in compost derived dissolved organic matter. Adapted from *Raber and Kögel-Knabner* [1997].

DOM Solution	Molecular weight fraction	K_{DOM}
Domestic Waste Compost	< 1 kDa	20,450
	1–14 kDa	19,769
	> 14 kDa	91,426
Plant Waste Compost	< 1 kDa	11,209
	1–14 kDa	11,629
	> 14 kDa	56,286

labeled organic contaminants applied to a compost feedstocks and tracked their subsequent fate and transformation during composting. Their results indicate that contaminants preferentially partition into DOM of particular molecular weight fractions. For example, pyrene preferentially partitioned into high molecular weight DOM, whereas di-2-ethylhexyl phthalate and simazine preferentially partitioned into lower molecular weight DOM.

The adsorption of organic contaminants, like pesticides, by DOM in compost leachates and use of composts to remediate contaminated soils have also been investigated [*Barriuso et al.,* 2011*; Caricasole et al.,* 2010*; Ertunc et al.,* 2002]. *Raber and Kögel-Knabner* [1997] studied the effect of DOM from composts as potential sorbents and carriers of hydrophobic polyaromatic hydrocarbons (PAHs). The authors found that the penta-cyclic PAH, benzo[k]fluoranthene showed a 4 to 5 times higher partition coefficient (K_{DOM}) in the high molecular weight DOM fraction compared to the lighter DOM fractions (Table 5).

5.3.4 Heavy (Trace) Metal Sequestration and Mobilization

Dissolved organic matter in compost leachate can effectively sorb and mobilize heavy metals. *Christensen and Tjell* [1984] conducted a study on 17 lysimeter columns containing composts of varying age and column lengths, and monitored for 7 heavy metals (Cd, Ni, Co, Zn, Cu, Pb, and Cr) in the leachate over a 30 month period. Simulated rainfall was applied weekly, amounting to 680 mm/yr. The initial leachate was found to exceed drinking water concentration standards for all metals, but the concentrations rapidly fell off within the first 6 to 18 months. After 18 months (450 mm leachate) only Ni was found to exceed concentrations allowed in drinking water standards. In the first year, the amounts of metals leached were as follows (as percent of the original content): Ni (1.9%), Co (1.3%), Cu (0.7%), Zn (0.4%), Cd (0.21%), Cr (0.1%), and Pb (0.07%). Interestingly, the amounts of heavy metal leached were only moderately correlated with compost origin, compost age, or lysimeter column packing depth.

Kaschl et al. [2002] applied municipal solid waste composts (65 tons/ha) to a calcareous, sandy soil (25 cm and 50 cm long columns) and a loamy soil (25 cm long column). They also applied compost extract to a non-calcareous sandy soil (25 cm long column). The compost-amended soils had significantly higher amounts of organic matter in the leachate than the non-amended soils. The higher amounts of dissolved organic matter in the leachate also contributed to a higher nitrate and metal (Cd, Cr, Cu, Hg, Pb, Ni, and Zn) mobilization.

The effect was less pronounced in the loamy than in the sandy soil, probably because the loam had more binding sites, e.g., clay particles, for organic matter and metal sorption. The study also indicated that soil minerals were re-absorbing the metals mobilized with the dissolved organic matter during the passage of the leachate, as 70% of the water extractable organic matter but only about 10% of the water extractable metals in the compost was recovered in the leachate. Only, Ni, Zn, Cu, and Cr were found to be leaching. The maximum release of the metals occurred within the initial 1 to 3 pore volumes of leachate; beyond that, the concentrations of the metals in the leachates dropped drastically, reaching a low ($< 10\%$ to 15% of peak) steady-state value. Thus, although considerable leaching did occur, most of the metals released with dissolved organic matter from the compost were accumulated in the topsoil underlying the compost layer [*Kaschl et al.,* 2002]. Similar accumulation of metals leached from compost into underlying soil has been reported by *Achiba et al.* [2009].

Chen et al. [2010] studied the leaching of Cu and Zn from an applied compost [equivalent to a surface application (no incorporation) of 65 tons/ha] into an underlying layer of red, clayey soil (Ultisol) in a 60 cm long laboratory column. Rainfall was simulated by irrigation, equivalent to a total of 200 mm rainfall in 5 events. The results indicated that 4% of the Cu and 58% of the Zn was leached out of the soil column. The soil column was subsequently sampled and tested for metal bioavailability using sequential extractions (as described in *Tessier et al.* [1979]). The extractions were conducted to determine the metal sorption in different soil constituents (e.g., residual formations, organic matter, Fe/Mn oxides, carbonates and exchangeable formations). The bioavailable heavy metals were usually from the sites which are exchangeable or where metals bound to carbonates. The bioavailability parameter, k, was defined as [*Chen et al.,* 2010]:

$$k = \frac{c_{ex} + c_{CO_3^{2-}}}{c_{total}} \tag{3}$$

where c_{ex}, $c_{CO_3^{2-}}$, and c_{total} are, respectively, the number of exchangeable sites, the carbonate-binding sites, and the total number of sorption sites (i.e., residual sites, organic matter, Fe/Mn oxides, carbonates and exchangeable sites). After the leaching experiments, about 75% of the total Cu and Zn added were found in the non-exchangeable, residual sites of the soil. The bioavailability of Cu and Zn ranged between $k = 0.05 - 0.10$ and $k = 0.09 - 0.16$, respectively. The bioavailability of Zn was higher than that of Cu in those treatments that had both Cu and Zn. Thus, the phytotoxicity of Cu is likely to be lower than that of Zn (assuming similar levels of toxicity in plants) when similar levels of contamination with the two heavy metals exist [*Chen et al.,* 2010].

Bolea et al. [2006] and *Bolea et al.* [2010] studied the distribution of a large group of ions between different fractions of organic matter extracted from compost. The authors found that the partition of ions into a specific fraction of the dissolved (or particulate) organic matter extracted from the compost depended upon speciation. *Bolea et al.* [2006] used ultrafiltration to separate different humic substances based on their molecular weights. The results showed that the inorganic species associated with three distinct molecular weight fractions of humic substances (<1 kDa, 1–50 kDa, and 100–300 kDa). Almost all monovalent metal ions, Mg^{2+}, and oxyanions preferentially bound to low molecular weight fulvic acids (Table 6). Most divalent metal ions, Cr^{3+}, and UO_2^{2+} bound to fulvic acids and humic acids.

Table 6: Elemental partitioning in humic substance fractions. Adapted from *Bolea et al.* [2006].

Group	Elements	Partitioning in humic acid fractions		
		<1 kDa (fulvic)	1–50 kDa (humic)	100–300 kDa (humin)
I	+1: Na, K, Rb, Cs +2: Mg oxyanions: As, B, Mo, W	>90%	–	–
II	+2: Ca, Sr, Co, Cu, Ni, Cd, Zn +3: Cr +6: U	30–81%	11–44%	Cd (17%), Zn (12%)
III	+1: Ag +2: Ba, Pb, Fe, Ce, Sn, Ti, La +3: Pb, Fe, Al, La, Ce, Ti, Bi +4: Ce, Ti, Zr, Sn, Th	<42%	16–50%	13–60%

Cd^{2+} and Zn^{2+} were the only exceptions showing significant binding to the highest molecular weight humin fraction. Other metals with oxidation numbers 3 or higher were binding to all three organic matter fractions (Table 6).

In a related study, *Bolea et al.* [2010] reported comparable results for metal uptake by organic matter in compost leachates fractionated by particle size [macromolecular (<15 nm), colloidal (15 nm–1 μm) and particulate (>1 μm)] rather than by molecular weight. These results suggest that if dissolved and particulate organic matter is leached from compost, colloid-facilitated transport of metals is likely to occur.

5.3.5 Nutrients in Compost Leachates

Many of the chemical species that leach out of compost, either in dissolved or particulate form, are plant nutrients. Dissolved and particulate organic matter in the compost leachate are important sources of C, H, N, O, and P. *Christensen* [1983] studied nutrient leaching from 3 and 12 month old composts made of equal parts of municipal solid wastes and waste-water sludge. The author reported that the outflow contained 100 to 400 mg/L of NH_4^+ during the first 100 to 300 mm of leachate. NO_3^- concentrations were 100 to 700 mg/L in the initial 200 mm of leachate, followed by a decrease in concentrations, and then by another surge in NO_3^- concentrations in the later 300 to 800 mm of leachate. These results indicate that compost leachates can contain considerable loads of nitrogen (in form of NH_4^+ or NO_3^-).

Christensen [1984] also investigated the leaching of a variety of other nutrients in compost. Table 7 lists the concentrations of these nutrients in cumulative compost leachate volumes, and Figure 4 illustrates the trends of nutrient concentrations as a function of cumulative leachate volume. These data show compost leachates can contain substantial amounts of nutrients, but that the nutrient concentrations in the leachate fall off quickly with volume of leachate.

The leaching of phosphorus out of compost is generally less pronounced than that of

Table 7: Nutrient concentrations in compost leachates. Adapted from *Christensen* [1984].

Nutrient	Cumulative leachate fraction		
	0–100 mm (mg/L)	100–200 mm (mg/L)	> 200 mm (mg/L)
Na	600–2100	50–600	0–400
K	200–1800	100–1200	40–700
Ca	250–1100	100–600	70–400
Mg	60–400	30–270	10–200
Mn	0.1–1.3	0.1–0.6	0–0.5
Fe	0.8–14	2–4	0.5–3.8
Cl	500-2500	40–800	0–500
SO_4^{2-}	180–1400	100–650	0–300
	0–100 mm	>100 mm	
PO_4^{3-}	1.2–17.5†	2.2–32.7†	
BO_3^{3-}	0.7–5.0†	0.7–5.0†	
F^-	0.3–22.7†	1.6–67.7†	

† Estimations based on values in Tables 1, 4, and 5 in *Christensen* [1984].

other inorganic ions. *Christensen* [1984] found that leaching of phosphorus was two orders of magnitude less than that of sodium, potassium, and calcium, all of which were present in similar initial percentages (per unit dry matter weight) in the compost. Phosphorus was considerably better retained by more mature composts (> 3 month old) as compare to less mature compost (< 3 months old). Less mature compost tends to leach more DOM, which can act as carrier of phosphorus, whereas mature compost showed less DOM leaching.

However, if the compost contains substantial amounts of phosphorus, like in animal manure-derived compost, phosphorus leaching can occur and cause pollution of surface and groundwaters [*Eghball,* 2003]. Studies on phosphorus leaching from compost-amended bioretention systems have shown mixed results. Some studies have shown that compost-amended bioretention systems can remove incoming phosphorus from stormwater [*Davis et al.,* 2006*; Hunt et al.,* 2006*; Davis,* 2007], some studies, however, showed net export of phosphorus [*Hunt et al.,* 2006]. Phosphorus export with effluent appears to be pronounced when the compost has high phosphorous content, and when the aeration of the test media is low, i.e., water saturation occurs [*Hunt et al.,* 2006].

Christensen and Tjell [1984] (see also Section 5.3.4) discussed the presence of other important plant micronutrients, e.g., Co, Cu, and Zn, in appreciable quantities in compost leachates. In a 9-year long study, *Miller et al.* [2013] monitored leaching of Ca, Mg, Na, K, and S from compost-amended soil cores. The authors found that composted manure showed more leaching of these ions than non-composted, but stock-piled manure. Excess leaching of nutrients causes harmful effects, indirectly through creating an ecological imbalance through promoting excessive growth of selected organisms, and directly because some nutrients, e.g., Cu, Zn, and Ni, become toxic when present at concentrations greater than physiologically necessary.

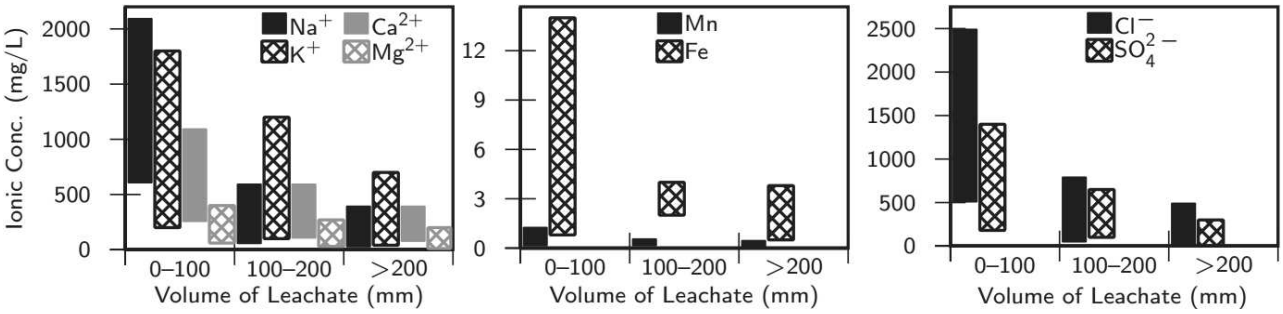

Figure 4: Nutrient concentrations in compost leachates. Drawn with data from *Christensen* [1984].

6 Implications and Conclusions

6.1 Leaching of Organic Matter and Nutrients

Compost is an important recycling product that helps to minimize and even eliminate organic waste by chemically transforming organic waste into a valuable soil amendment. Provided that the compost itself does not contain any toxic chemicals, the application of compost to the environment is generally beneficial; however, the leachates coming out of compost nonetheless can be of environmental concern. The reviewed literature indicates that materials can readily leach out of compost. The leachate is composed mainly of dissolved and particulate organic matter. Along with dissolved and particulate organic matter, nutrients—either as components of organic matter molecules or associated with exchange sites on organic matter—are leaching. The exact chemical makeup of the leachate varies with type of feedstock as well as age and maturity of the compost. The initial leachate contains the highest concentrations of dissolved and particulate matter and nutrients, and with increased amount of water passing through the compost, the amount of leached materials decreases.

There are only few comprehensive studies where leachates from compost have been analyzed as a function of leachate volume and time. Although some generalizations can be drawn from these studies (e.g., considerable amounts of organic matter and nutrients, including nitrogen and phosphorus, can be readily leached in the initial flushes), each compost feedstock and compost maturity will be different, so that specific studies with a given compost material would be required to assess the exact quantity and nature of materials leached from a given compost.

6.2 Facilitated Leaching and Retention of Organic Contaminants and Metals

Besides the dissolved and particulate organic matter, compost leachate may, depending on the feedstock source, contain organic and inorganic contaminants (toxic organic chemicals—such as for instance pesticides, surfactants, halogenated hydrocarbons—and metals). The leached dissolved and particulate organic matter can facilitate the movement of organic contaminants and metals that are otherwise relatively immobile in compost. Along with the initial, enhanced leaching of the dissolved and particulate organic matter, these organic

contaminants and metals likely show increased leaching in the initial flushes of compost through the process of colloid-facilitated contaminant transport.

On the other hand, the stable, non-leachable organic matter can retain organic contaminants and metals by the process of sorption. Compost therefore plays a role in sequestering organic contaminants and metals. Compost is used as soil amendment to help remediate contaminated water, e.g., stormwater runoff from paved areas like parking lots and roadways. The large number of sorption sites in organic-matter-rich media, like compost, provides a means to control runoff of organic contaminants and metals, at least initially until the compost is being decomposed and mineralized, or until the sorption sites in the compost are saturated. Organic contaminants retained in compost can, over time, be metabolized by microorganisms or degraded by chemical processes. However, some more recalcitrant organic contaminants can be partitioned into the organic matter in such a way that the contaminants are protected from microbial degradation.

6.3 Bioavailability and Toxicity

The nature and characteristics of the compost leachate, especially after compost is applied, is of prime importance because the leachate from compost is the component that has an off-site effect on the surrounding environment. Compost can contain both organic and inorganic contaminants, and these are inevitably introduced to the environment when contaminated compost is applied as soil amendment. Through decomposition of organic matter in the compost, contaminants can become increasingly bioavailable and can even leach from the compost. This is particularly relevant in the case of heavy metals, which readily combine with dissolved organic matter and thereby become bioavailable for aquatic organisms. The presence of heavy metals and environmentally persistent toxic organic compounds should therefore be monitored from the feedstock selection, processing and mixing stages itself, so that the levels of these undesirable components are kept under toxicity limits in the final matured compost product.

7 Research Needs

This review indicates the need of undertaking a series of studies on the nature of the compost leachates keeping a close control over the feedstock and the composting process (e.g., temperature, aeration, moisture levels, and microbial activity). Such studies, conducted over a wide variety of feedstock types, especially considering the current nature of municipal and small-scale industrial feedstock types, are necessary to accurately calibrate the process parameters for producing composts of appropriate properties. Composts find a wide variety of uses, so there is an opportunity to customize the composting process and the product compost for the target usage in mind. This will not only ensure the best performance of the applied compost to the usage scenario, but also make the application of composts more widespread and functional.

Based on this literature review, we see the need to clarify the nature and role of compost leachates and to identify means to minimize leaching of materials from applied compost. Specific research questions should address the following:

1. Characterize and quantify compost leachates in terms of a series of constituents (e.g., organic matter, nutrients, heavy metals, organic contaminants) from specific feedstock according to:
   (a) Differences in feedstock mixes
   (b) Feedstock properties (e.g., C/N ratio, moisture content)
   (c) Compost maturity and type (process methods, curing period, temperature, and aeration control)
   (d) Amount of water leaching through compost
2. Characterize compost interactions with contaminated runoff from a variety of sources
3. Categorize compost leachates from specific feed stock mixes according to
   (a) Potential for heavy metal and toxic organic compound retention
   (b) Phytotoxicity
   (c) Bioavailability of contaminants
   (d) Bioavailability of leached nutrients

Laboratory batch and column studies can be used to address the research topics listed above. Compost leachates and leachate-metal interactions can be characterized spectroscopically (UV/Vis, FTIR, Mössbauer, NMR) and with standard chemical techniques (C/N ratio, pH, electrical conductivity, metal contents). Different compost materials can be packed into laboratory columns and controlled irrigation can be used to leach the compost. Column outflow can be sampled incrementally with a fraction collector and characterized for chemical and physical properties as a function of outflow volume.

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9 List of Abbreviations

Abbreviation	Expanded form
2,4-D	2,4-Dichlorophenoxyacetic acid
A	UV/Vis Absorbance
BMP	Biochemical Methane Production Potential
BOD	Biological Oxygen Demand
C/N ratio	Carbon-to-Nitrogen ratio
COD	Chemical Oxygen Demand
DDE	Dichloro Diphenyl Dichloro-Ethylene
DDT	Dichloro Diphenyl Trichloroethane
Dicamba	3,6-Dichloro-2-Methoxybenzoic Acid
DGGE	Denaturing Gradient Gel Electrophoresis
DNA	Deoxy Ribonucleic Acid
DOC	Dissolved Organic Carbon
DOM	Dissolved Organic Matter
EC	Electrical Conductivity
FA	Fulvic Acid
FT-IR	Fourier Transform-Infra-Red
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectroscopy
(k)Da	(kilo) Daltons
k	Bioavailability Parameter
K_{DOM}	Partition Coefficient between Water and Dissolved Organic Matter
LWCA	Low-Weight Carboxylic Acid
MW	Molecular Weight
Mecoprop	Also known as MCPP, Methyl Chloro Phenoxy Propionic Acid
NMR	Nuclear Magnetic Resonance
PAH	Poly Aromatic Hydrocarbon
PCB	Poly-Chlorinated Biphenyls
R–	Alkyl Functional Group
rDNA	Ribosomal DNA
RNA	Ribonucleic Acid
rRNA	Ribosomal RNA
SMS	Spent Mushroom Substrate
UV/Vis	Ultraviolet/Visible
WEOM	Water Extractable Organic Matter
XAD	Trade name for a series of proprietary ion-exchange resins based on derivatized polystyrene (Dow Chemicals)

10 Glossary

C/N ratio	The ratio of carbon-to-nitrogen, on a per weight basis, present in a sample, usually measured in soils, sediments, and composts.
functional group	A specific group of atoms or bonds within a molecule which are responsible for characteristic chemical properties and reactions. Functional groups can interact with each other to modify their reactivity. (IUPAC)
moiety	A part of a molecule containing whole or partial functional groups as a substructure. (IUPAC)
aliphatic group	A hydrocarbon group consisting of carbon and hydrogen in a straight or branched chain configuration, the chains may or may not contain multiple bonds between carbons, but does not contain aromatic (e.g., like benzene) rings.
phenol	A class of organic compounds containing one or more—OH functional groups attached directly to a carbon in an aromatic (benzene) ring. The equivalent functional group is called a phenyl group.
meso-organism	A living organism which is large enough to be visible to the naked eye, usually larger than a few hundred μm to a few cm in size. The range is, however, somewhat context sensitive.
colloid	A particle in the size range 1 nm to 2 μm, which is too large to form a truly dissolved species in a solvent, and too small to settle as a sediment. Dispersions of colloidal particles scatter light (visible, UV, IR) rather than transmitting it.
nitrogen mineralization	The process in which organic forms of nitrogen (e.g., proteins in dead plant and animal material) are converted by microbial degradation and uptake to inorganic forms of nitrogen (e.g., ammonium and nitrate).

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