University of Alberta

Evaluation of the Impact of Contaminant on Trace Metal Content of Compost

by

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Abstract

Literature reviews indicated that batteries, ferrous, non-ferrous materials, and electronic products are major contributors of trace metals in municipal solid waste (MSW). In order to assess the impact of various contaminants on the trace metal content of compost, contaminants including alkaline batteries, galvanized nails, Zn-plated screws, copper wires and electronic cables were exposed to a thermophilic composting process for three weeks. The increase in trace metal content in the compost product was measured, after the composting process. The results showed that the main contributors of trace metals are copper wires and galvanized nails. They contributed 51.9% of the CCME A limit for copper and 29.5% of the CCME A limit for zinc, respectively. To ensure the compost quality reaches the CCME category A criteria, contaminants made from bare copper or coated with zinc should be removed from the composting feedstock as much as possible.

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List of Symbols, Nomenclature, and Abbreviations

α	significance level for a statistical test
ºC	degrees Celsius
Φ	diameter
ACQ	alkaline copper quaternary
ANOVA	analysis of variance
BD	bulk density
CCA	chromated copper arsenate
CCME	Canadian Council of Ministers of the Environment Canadian
CIFA	Canadian Food Inspection Agency
cm	centimetre
db	dry basis
dw	dry weight
EC	electrical conductivity
ECF	Edmonton composting facility
EDX	energy dispersive x ray spectrometer
g	gram(s)
GC	gas chromatography
Hp	high pH
IC	ion chromatography
kg	kilogram(s)
Lp	Low pH
m	metres
MC	moisture content
min.	minute
mm	millimetre
ms	millisiemens
MSW	municipal solid waste
NACE	National Association of Corrosion Engineers
No.	number

P	P-value
PTE	potential toxic element
SD	standard deviation
SEM	scanning electron microscope
TMECC	Test Methods for the Examination of Compost and Composting
USEPA	United States Environmental Protection Agency
wb	wet basis
ww	wet weight
XRD	x-ray diffractometre

CHAPTER 1 INTRODUCTION

1.1 Background

1.1.1 MSW and MSW Composting

Municipal solid waste (MSW) is a mixture of both organic wastes such as food wastes, yard trimmings, and inorganic materials such as plastics, glass and metals. Regarding MSW composting, the inorganic portion is non-compostable and is seen as the source of the potentially toxic elements (PTEs) which may accumulate in the compost product and create detrimental effects in the environment (Richard and Woodbury 1992). Since compost is used as a soil amendment, its quality is ensured by setting up standards and regulations. Among all the quality criteria, the PTE content is important in compost classification (Ge et al. 2006). In order to reduce the level of PTEs, the inorganic portion is removed from the organic through many approaches. Two approaches are mainly applied in MSW composting facilities - source separation of organic wastes and centralized separation of mixed MSW (Harrison and Richard 1992).

1.1.2 Edmonton Composting Facility

The Edmonton Composting Facility (ECF) has been operating for about ten years using mixed MSW as the composting feedstock. As the largest MSW composting plant in North America, it has the capacity of processing 200,000 tonnes (wet weight) of residential waste and 22,500 tonnes (dry weight) of sewage biosolids each year (City of Edmonton 2009). It is estimated that together with the recycling program, approximately 60% of the residential waste is diverted from the landfill and 80,000 tonnes of compost are produced annually. The composts have been sent to market: used by farmers, landscapers, nurseries and oilfield reclamation companies (City of Edmonton 2003). As a successful example of a mixed MSW composting facility, the ECF shows that MSW composting is an economical and environmentally friendly alternative to landfill (Goldstein 2000).

However, similar to other mixed-waste MSW composting facilities, the ECF also has to face the challenge of compost quality. Eleven trace elements including arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se) and zinc (Zn) are listed as PTEs in the Canadian Council of Ministers of the Environment (CCME) Compost Quality Guidelines (CCME 2005). The concentration of 11 trace elements of the ECF compost is in compliance with the CCME Category B criteria (Table 1-1). Five trace elements in the compost product have prevented the ECF from achieving a Category A designation. These elements are zinc, copper, nickel, molybdenum and selenium (City of Edmonton 2009).

Table 1-1 Comparison of trace elements content in ECF compost to the CCME guideline and CFIA standard.

Trace Element	CCME Category A Limit (mg kg^{-1} dry weight)	CCME Category B Limit (mg kg^{-1} dry weight)	CFIA Maximum Acceptable Cumulative Additions to Soil (kg ha^{-1})	Edmonton Composting Facility [a] (mg kg^{-1} dry weight)
As	13.0	75.0	15	3.12
Cd	3.0	20.0	4	2.33
Co	34.0	150.0	30	5.90
Cr	210	N/A	210[b]	101.43
Cu	400.0	N/A	150[b]	544.96
Hg	0.8	500.0	1	0.68
Mo	5	5.0	4	5.61
Ni	62	20.0	36	89.11
Pb	150	180.0	100	132.19
Se	2.0	14.0	2.8	2.35
Zn	700	1850.0	370	1296.72

Note: [a] Average trace element concentration of ECF compost (City of Edmonton 2009; Table C1); [b] CFIA internal standards (CFIA 2009); N/A-Not available.

The Canadian Food Inspection Agency (CFIA) established standards for the maximum acceptable cumulative metal additions to soil (Table 1-1) in the CFIA Trade

Memorandum T-4-93 (CFIA 1997). According to these standards, copper and zinc are the primary trace elements that limit the application of the ECF compost.

1.1.3 Trace Metals in MSW Compost

The majority of the trace elements listed in CCME guidelines are heavy metals (density greater than 5 g cm^{-3}). Since they are all present in compost at low concentrations, they are referred to as trace metals. Studies by Woodbury (1992) revealed that the trace metal content in compost produced from mixed MSW is higher than the compost produced from the source separated organic wastes. The repeated application of MSW composts in agriculture and horticulture resulted in high trace metal accumulation in the soil (Woodbury 1992; Madrid et al. 2007). Therefore, in order to broaden the application of MSW compost and enhance its economic value, the trace metal content is a critical issue that must be addressed.

1.2 Research Goals

A project was initiated to investigate the impact of pre-treatment on the quality of compost from mixed MSW. The purpose of the project was to find the potential benefits of pre-treatment and feedstock manipulation on compost quality with a particular emphasis on trace metal levels (Ge 2005). Being part of the project, this research consists of a literature review on the sources of trace metals in mixed MSW and two trials of experiments which were carried out to investigate the impact of various contaminants on the compost quality.

The objectives of this research were to: (1) identify the main contributors (contaminants) of high trace metal content in mixed MSW composting feedstock, (2) quantify the trace metal mass transfer from the contaminants, and (3) evaluate the impact of each contaminant on the trace metal content in composts.

1.3 Principle Results and Conclusions

A literature review was conducted to investigate the main contributors (contaminants) of high trace metal content in mixed MSW. Studies from US (Rugg and Hanna 1992) and Switzerland (Maystre and Viret 1993) suggested that batteries, ferrous, non-ferrous materials and electronic products are the major metal contributors in MSW. During the composting process, metals could be released from the contaminant to the compost through physical, chemical and microbial reactions. All three of these pathways can be explained by the corrosion theory. Through the introduction of the corrosion theory and corrosion mechanisms in a composting environment, the corrosion weight loss measurement was proposed as the primary method to determine the metal mass transfer in the composting environment.

The first trial of the experiment was carried out by exposing six types of contaminants (galvanized nails, Zn-plated screws, stainless steel flat washers, copper wires, brass screws and light bulb tails) to a low pH and high pH feedstock for a three-week thermophilic composting process. The result of contaminant weight losses suggested that composting substrate with a lower pH value could lead to a higher metal mass transfer. Zn-plated screws and galvanized nails showed the highest weight loss values, while stainless steel flat washers and light bulb tails showed little weight changes. The determined mass transfers of zinc from galvanized nails, Zn-plated screws, and copper from copper wires were used in the experimental design of contaminant addition in the second trial.

In the second trial of the experiment, contaminants including high quality alkaline batteries, low quality alkaline batteries, copper wires, electronic cables, galvanized nails and Zn-plated screws were exposed to a low pH feedstock for a three-week composting process. The trace metal content in the composts was determined. Concentrations of trace metal arsenic, cobalt, copper, lead and zinc in the composts were significantly increased after composting. The low quality batteries were found to have a significant effect on the increase of arsenic and cobalt content. Galvanized nails and copper wires were found to have a significant effect on the increases of zinc and copper, respectively. Contaminants made from bare copper and with zinc coating could contribute to a high level of zinc and copper in the compost product.

1.4 Thesis Organization

According to the University of Alberta's "paper" format, the first chapter introduces the project's background and research goals. The final chapter (chapter 5) is a general discussion of the results from each chapter and the correlation among them.

Chapter 2 is a literature review on trace metal contamination of MSW compost. The main contributors of trace metals in MSW are indentified and the conceptual pathways of trace metal contamination of compost are proposed.

Chapter 3 is the first trial experiment applying the corrosion weight loss measurement method to determine the metal mass transfer from six types of contaminant.

Chapter 4 is the second trial experiment, which is aimed at evaluating the impact of six types of contaminants on the trace metal content in composts and suggesting the main contributors of the high trace metal content in composts.

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CHAPTER 2 A REVIEW OF TRACE METAL CONTAMINATION OF MSW COMPOST

2.1 Introduction

The potentially toxic element (PTE) content of compost is a concern due to potential toxicity to plants, animals and humans (Woodbury 1992; Madrid et al. 2007). For example, although trace amounts of metals, such as zinc (Zn), copper (Cu) and nickel (Ni) are beneficial for plant growth, they can accumulate in soil if application rates are higher than the plant needs (Richard and Woodbury 1992; Woodbury 1992), which may have a detrimental effect on plant growth (Whittle and Dyson 2002). Also, nonessential metals, such as cadmium (Cd), mercury (Hg) and lead (Pb) can be phytotoxic at trace concentrations (Lal 2006). Because of this potential toxicity, environmental protection guidelines have been set out to ensure the application of compost is done in a safe manner. In Canadian guidelines, eleven elements including arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se) and zinc (Zn) are listed. Since they are present in composts at a low concentration, they are referred to as trace elements (Ge et al. 2006). Several trace elements listed in the guidelines are heavy metals (density greater than 5 g cm^{-3}). In this review, the term trace metal refers to heavy metal, which is presented at trace concentration in compost products.

In Municipal solid waste (MSW) composting, the sources of the composting feedstock can be mainly classified into two categories - separated organic wastes and mixed MSW (Richard and Woodbury 1992). For the latter, the presence of trace metals raises concern in the MSW compost quality (Richard and Woodbury 1992; Madrid et al. 2007). The main contributor (contaminant) of trace metals in MSW is an important issue to be addressed in this review.

The corrosion phenomenon is common in composting facilities since the composting environment is very humid and contains abundance of corrosive species (Sherman 2003;

Emerson 2005). The pathways of metal release from the contaminant to the compost (organic fraction) were summarized in this review, which are essentially physical, chemical and microbial reactions. All these reactions can be explained by corrosion theory. Thus, an introduction of corrosion mechanisms in the composting environment is also included in this review.

The purpose of this review is to: 1) investigate the main contributors (contaminants) of high trace metal content in mixed MSW; 2) summarize the pathways of metal transfer from the contaminant to the compost (organic fraction) and 3) introduce the corrosion theory as the primary method of determining metal mass transfer in the composting environment.

2.2 Regulations and Standards on Compost Quality

Regarding the risk associated with the land application of composts, compost quality is addressed by the establishment of several classes and restrictions in its uses (Harrison and Richard 1992). Three national organizations are involved in establishing compost standards in Canada. The Canadian Food Inspection Agency (CFIA) regulates compost under the authority of the Canadian Fertilizer Act (CFA). The Bureau de normalization du Quebec (BNQ) which is a member of the Standards Council of Canada (SCC) has established voluntary standards for compost quality, and is available to composters across Canada. The Canadian Council of Ministers of the Environment (CCME), which is the organization that establishes harmonized nationwide environmental standards, also established the Guidelines for Compost Quality. Composts are classified based on their quality. In the CCME Guideline, the trace element concentration is the major criterion that differentiates composts between category A and category B (Ge et al. 2006). Eleven trace metals are included in the above standards, they are: arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), mercury (Hg), molybdenum (Mo), nickel (Ni), lead (Pb), selenium (Se), and zinc (Zn). Three approaches are used to set the standards of trace element concentration: (1) the no net degradation (NND) approach, (2) the risk-based approach, and (3) the best achievable technology (BAT) approach. The NND approach is the most conservative one. It is combined with the BAT approach to set compost standards in Canada. The risk-based approach is applied to set limits for sewage sludge by the United States Environmental Protection Agency (USEPA). The limits are more permissive than those set by the other two approaches. The maximum concentration limits for these heavy metals vary in different jurisdictions (Ge et al. 2006).

2.3 MSW Composting Separation Strategies

In order to minimize contaminants in MSW, several approaches are applicable (Richard and Woodbury 1992):

1. Reduce or eliminate contaminant levels in products destined to become MSW
2. Source separate clean organic materials for separate collection and composting
3. Source separate contaminants for separate collection and disposal
4. Separate contaminants form MSW at a centralized facility prior to composting
5. Separate contaminants from MSW compost at a centralized facility after composting

Except for the first approach, which is beyond the control of composting facilities, all the other options are widely applied and can be divided into two categories - source separation and centralized separation. The source separation approach limits the composting input feedstock to organic wastes only. The centralized separation strategy uses mixed MSW as the feedstock. The non-organic fraction is separated either before or after composting by manual picking, magnetic separation, air classification or other mechanical approaches.

Richard and Woodbury (1992) summarized the results from several comparative studies to evaluate the impacts of separation approaches on MSW compost trace metal content (Table 2-1). Studies 1 and 2 were carried out in The Netherlands. Similar trends of metal concentrations were observed. The levels of all metals in the compost produced from source separated organic waste were much lower than the values from centralized separation. The highest levels were found from the separation approach with the screening of the finished compost only. Study 3 was conducted in Germany. The results were consistent with the conclusion from study 1 and 2.

Table 2-1 Comparative studies on trace metal content (mg kg^{-1} dry weight) of MSW compost product (Richard and Woodbury 1992).

Study	Separation Approach	Cd	Cr	Cu	Ni	Pb	Zn
1	source separation	0.8	43	35	N/A	130	195
	central separation	1.8	46	177	N/A	600	640
	final product screening only	8.5	140	530	N/A	830	1600
2	source separation	1	30	50	10	160	230
	central separation	2.15	55	185	30	560	660
	final product screening only	7	180	600	110	800	1700
3	source separation	1	36	33	29	133	408
	central separation	5.5	71	274	45	513	1570

Source separation strategy is regarded as the best option to achieve lowest levels of trace metals. However, as a trade off, it is less convenient for the household collection and public education is required (Harrion and Richard 1992). The compost produced from centralized separation processes raises more quality issues than the compost made from source separated organics. But it is more efficient in achieving high diversion rates (Richard and Woodbury 1992). With respect to the designing of the separation method for a composting facility, factors such as compost quality, waste quantity and cost should all be taken into consideration.

2.4 Contributors of Trace Metals in the Mixed MSW Composting System

Wastes generated in daily life, such as scrap steels, iron cans, metal wires and plastics may contain a high level of heavy metals. In spite of many recycling programs put in place, they can still get into the waste stream. Once they are involved in the composting process, they are considered contaminants. In order to investigate the impact of different contaminants on the trace metal levels of the waste stream, many studies on the characterization of MSW were carried out. Based on the studies from United States (Rugg and Hanna 1992) and Switzerland (Maystre and Viret 1993), contaminants that contributed to the trace metal content in MSW are presented in Table 2-2 (Ge 2007). The ranking is based on the contribution of the waste material to the total metal content.

Table 2-2. The contribution of contaminants to trace metals in MSW.

Ranking	**Contaminant**	**Contribution of the contaminant to the trace metal content in MSW (% of total of the element)**	
		Swiss study Maystre and Viret (1993)	**US study Rugg and Hanna (1992)**
1	Batteries	Zinc-carbon and alkaline: Hg: 98%; Zn: 40%	Hg: 89% Zn: 55%
2	Ferrous materials except metal cans	Not reported	Cd: 16% ; Cr: 85% ; Ni: 50% ; As: 19% ; Zn: 10%
3	Non-ferrous materials	Non-ferrous metals: Cu: 43%; Zn: 32%; Pb: 17%	Non-ferrous (excluding aluminum): Cd: 18% ; Cu: 85% ; Pb: 52% ; Ni: 30% ; Zn: 9%
4	Electronic products	Cu: 32% ; Zn: 12%; Cd: 22%; Pb: 16%	Not reported
5	Treated woods	Not reported	As: 58%
6	Glass	Pb: 39% (mainly due to lead bottle capsules)	Pb: 3%
7	Plastic scraps	Cd: 39%	Not reported
8	Other paper (excluding newspaper and packaging paper)	Cu: 12% Cd: 14%	Cu, Zn, Cd, Hg, or Pb: <6%
9	Leather-rubber scraps	Cu, Zn, Cd, Hg, or Pb: <4%	Not reported
10	Textiles	Cu, Zn, Cd, Hg, or Pb: <0.2%	Not reported
11	Other items	Cu, Zn, Cd, Hg, or Pb: <5%	Not reported

2.4.1 Batteries

Batteries even at a high recycling rate are a significant source of trace metals in the municipal solid waste stream (Richard and Woodbury 1992). For instance, the study conducted by Rosseaux et al. (1989) revealed that batteries contributed the greatest part of metals (including 93% mercury, 45% cadmium, 45% zinc and 20% nickel) in French household wastes. The study conducted by Maystre and Viret (1993) indicated that zinc-carbon batteries and alkaline batteries contributed 98% mercury and 40% zinc. Rugg and Hanna (1992) indicated that household batteries contains 2900 mg kg^{-1} mercury, 180000 mg kg^{-1} zinc, which contributed 89% of mercury and 55% of zinc to the waste stream.

2.4.2 Ferrous and Non-ferrous Materials

Metal and metal alloys are widely used in today's society. Steel contains at least 50% iron and one or more alloying elements. The alloying elements generally include carbon, manganese, silicon, nickel, chromium, molybdenum, vanadium, titanium, niobium, and aluminium (Ge 2005). The residual elements in steel include tin, antimony, arsenic, and copper. Leaded steels contain 0.15–0.35% lead for improved machinability. Stainless steels are corrosion-resistant steels that contain at least 10.5% cadmium (Ge 2005). The US study (Rugg and Hanna 1992) suggested ferrous materials as an important source of metals including cadmium, zinc, chromium, arsenic and nickel. While in the Swiss study (Maystre and Viret 1993), ferrous materials were not included as a separate category.

2.4.3 Electronic Products

The category of electrical and electronic products includes household appliances, information technology equipments, audio-visual equipments and leisure equipments, which contain trace metals such as lead, mercury, cadmium and arsenic (Ge 2005). Polyvinyl chloride (PVC) plastics are commonly used in electronics cabling, wiring and housing. In some PVC products, trace metals such as lead and cadmium are often added to make them more durable (Ge 2005). In the Swiss study (Maystre and Viret 1993), electronic products contributed 32% copper, 12% zinc, 22% cadmium and 16% lead to the MSW. In the US study, electronic products were not included as a separate category.

2.4.4 Others

The US study (Rugg and Hanna 1992) indicated that treated wood contributed to 58% of arsenic in MSW. Due to the lead bottle seal, glass contributed to 39% of lead in the Swiss study (Maystre and Viret 1993). While in the US study, glass contributed only 3% of lead. Both US and Swiss studies reported that plastic scraps was a significant contributor of cadmium in MSW. Paper, leather-rubber scraps and textiles contributed a low level of metals including copper, zinc, cadmium, mercury and lead to the waste stream.

Except for the products analyzed above, products with paint or ink also contain metals from the pigments (mercury, cadmium, zinc, lead, chromium, copper, cobalt, etc.) (Ge 2005). The significance of these metals' contributions to the metal content in MSW depends on the specific situation such as the amount of paint or ink in the product.

It should also be mentioned that consumer products have undergone significant changes due to improvement in technology and enhancement in environmental regulations. For example, current alkaline batteries are mercury free; new treated wood products contain no arsenic due to the fact that Alkaline Copper Quaternary (ACQ) preservative has replaced Chromated Copper Arsenate (CCA); and plastic (instead of lead) bottle capsules are now commonly used. It can be expected that some of the current consumer products (such as alkaline batteries and treated wood) contain a lower metal content than those reported in these studies (Ge 2007).

2.5 Pathways of Trace Metal Contamination in MSW Compost

Once the contaminants are mixed with the organics in the MSW stream, they may potentially release metals to the compost material (organic fraction) through three pathways: chemical reaction, microbial activity, and physical abrasion. Information on the mechanisms of trace metal contamination in composts was summarized based on knowledge in soil science, environmental chemistry, geochemistry and MSW composting technology. The conceptual pathways of trace metal contamination are illustrated in Figure 2-1 (Ge 2007).

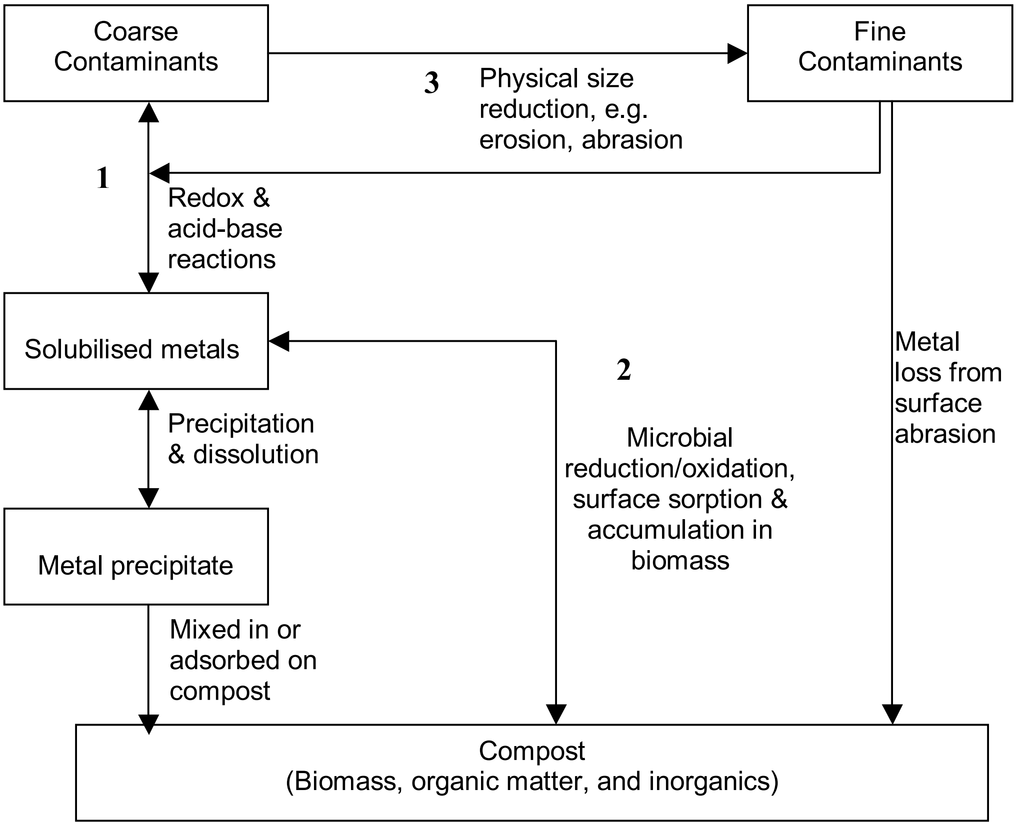

Figure 2-1 Pathways of metal transfer from contaminants to compost products. 1: chemical reactions; 2: microbial activities; 3: physical abrasion (arrows in the figure indicate the metal transfer direction.

(1) Chemical Reactions

As illustrated in Figure 2-1, chemical reactions, such as reduction-oxidation reactions (redox) and acid-base reactions can transfer heavy metals from the surface of contaminants to a soluble form (e.g. $Zn^0 \rightarrow Zn^{2+}$, $ZnO + 2H^+ \rightarrow Zn^{2+} + H_2O$). The solubilised metals then precipitate as hydroxides and carbonates, which will be adsorbed on the compost matrix and therefore increase the metal levels in compost products (Flyhammar 1997). The organic matter present in the waste can also bind with metals to form complexes, which would increase the solubility of heavy metals, especially in a high pH environment (Leita and Nobili 1991).

(2) Microbial Activities

Composting is essentially a biological process, in which microorganisms play an important role. According to Ahmad et al. (2005), microbes are also highly involved in the reactions of metal immobilization during composting processes; for example: direct microbial oxidation or reduction of the metals, direct sorption by microbial biomass, uptake and bioaccumulation of metals, indirect microbially mediated changes in metal redox state (e.g. iron reducing bacterial), and indirect stimulation of mineral precipitation by microbial surfaces. Additionally, microbial metabolism can also produce complexing ligands which can immobilize metals through precipitation. Once contaminant metals are mixed with the organics, they will accumulate and will end up in the compost product.

(3) Physical Abrasion

Erosion and abrasion can happen once the contaminants are mixed with the clean organic waste. For example, abrasion may occur during waste handling, which can break off bits of lead from foil (Richard and Woodbury 1992). Abrasion can also cause contaminant size reduction. Once fine contaminants are mixed with the organic material, they are difficult to screen out and will contribute to the total metal content in compost products.

2.6 Corrosion in a Composting Environment

Corrosion is an issue that should be addressed in many composting facilities since it can cause deterioration of the building materials, especially for indoor composting facilities. According to Emerson (2005), serious corrosion occurred to a 10-year-old biosolids composting operation in Davenport, Iowa, although the building's interior was epoxy-coated. The enclosed composting environment is inherently corrosive due to the high indoor humidity, corrosive gases such as ammonia and hydrogen sulphide, and an abundance of bacteria (Sherman 2003; Emerson 2005). The corrosion control for the building material is therefore important to the composting facility operators.

In this review, the study of the basic corrosion theory is aimed at understanding the behaviour of metals transferring from the contaminant to the organic fraction of compost through corrosion. The theory also supports the method of quantifying the metal mass transfer during the composting process.

2.6.1 Basic Corrosion Theory

Corrosion can be defined as a chemical or electrochemical reaction between a material, usually a metal, and its environment that produces a deterioration of the material and its property (Davis 2000). The formation of a corrosion cell which is comprised of the anode, cathode, electrolyte and metallic path is essential for corrosion to take place (Ahmad 2006).

The reactive metal is dissolved at the anode and oxidized to a higher valence state. The anodic reaction in terms of electron transfer is written as:

$$M \longrightarrow M^{n+} + ne$$

Reduction takes place at the cathode and the most common cathodic reactions in terms of electrons transfer are (Ahmad, 2006):

a) $2H^+ + 2e \longrightarrow H_2$ (in acid solution)
b) $O_2 + 4H^+ + 4e \longrightarrow 2H_2O$ (in acid solution)
c) $2H_2O + O_2 + 4e \longrightarrow 4OH^-$ (in neutral and alkaline solutions)
d) $Fe^{3+} + e \longrightarrow Fe^{2+}$ (metal ion reduction in ferric salt solutions)
e) Metal deposition: $M^{2+} + 2e \longrightarrow M$
$Ni^{2+} + 2e \longrightarrow Ni$
$Cu^{2+} + 2e \longrightarrow Cu$
f) Bacterial reduction of sulphate: $SO_4^{2-} + 8H^+ + 8e \longrightarrow S^- + 4H_2O$

During aerobic composting, contaminants are mixed with various species in a moist condition. Corrosion arises in such aqueous environment with the formation of anodic and cathodic areas on the contaminant's surface. Electrochemical reactions are accelerated. The anode, cathode and electrolyte as a whole are called a corrosion cell. According to Ahmad (2006), two types of corrosion cells can be formed in the composting environment, which are:

a) Galvanic cells

Galvanic cells (Figure 2-2) are composed of either dissimilar metals acting as both the anode and cathode in an electrolyte, or the same metal in dissimilar conditions in a common electrolyte. The different electrochemical potential is the driving force for the corrosion to take place. The tendency of a metal to corrode in a galvanic cell is determined by its position in the galvanic series.

This type of corrosion cell represents the general corrosion reactions that can lead to metal loss from the contaminant. The released metals are then transferred to the composting environment.

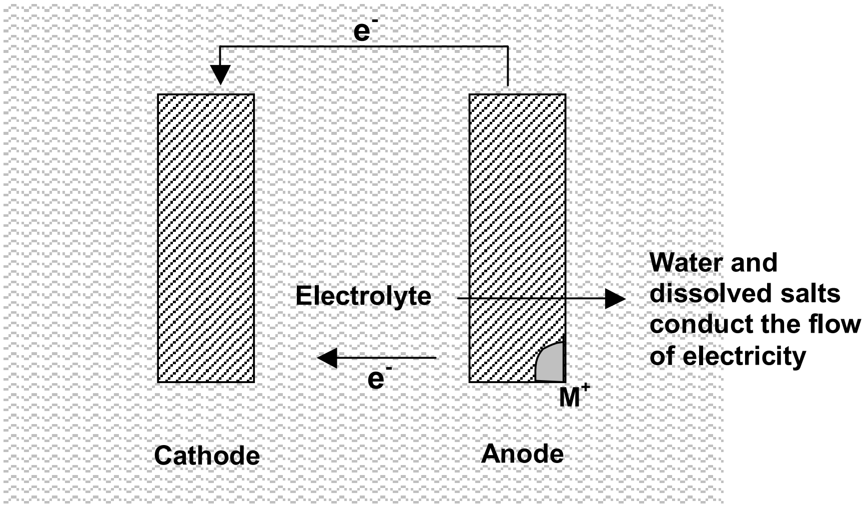

Figure 2-2 Typical galvanic cell (Adapted from Ahmad 2006).

b) Concentration cells

Concentration cells (Figure 2-3) refer to an anode and cathode of the same metal in a heterogeneous electrolyte. Differences in the amount of oxygen, moisture content, and compositions of the electrolyte are the key elements for the set up of a concentration cell. The Nernst equation can be used to determine the electrode potential in a concentration cell (Davis 2000).

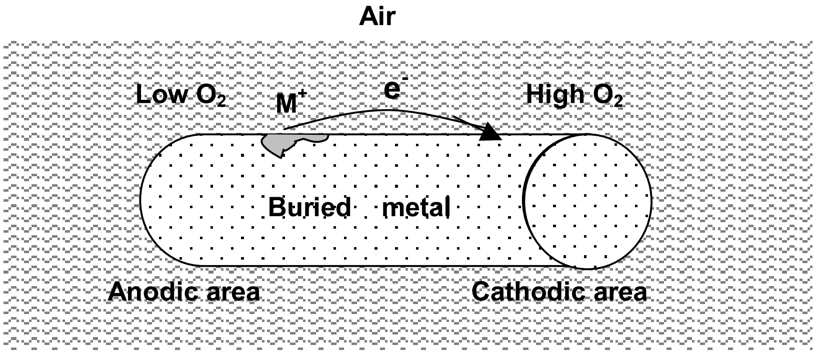

Figure 2-3 Concentration cell formation for a buried metal (Adapted from Ahmad 2006).

The concentration cell is likely to be formed when the aeration inside the composting pile is different, or the composting substrate is highly heterogeneous. Metal ions tend to be released to the surrounding materials.

2.6.2 Corrosion Influencing Factors in a Composting Environment

There is usually a combination of variables, for instance, aeration, pH, temperature, moisture content and microbial activity, which can significantly alter the corrosion behaviour of the contaminants in the MSW. According to Davis (2000), the following are the key factors that can affect the corrosion rate under a composting condition:

1) Relative degree of acidity or alkalinity
2) Temperature
3) Degree of aeration
4) Presence of detrimental / beneficial species
5) Moisture, and

6) Microbial activity

2.6.2.1 Acidity and alkalinity

Among all these influencing factors, acidity and alkalinity can affect the solubility of corrosion products, the nature of microbial activity, as well as the oxidizing/reducing characteristics in the corrosion environment. An acidic environment usually represents a higher corrosion risk to common construction materials such as steel and zinc coated steels. According to Ahmad (2006), the galvanic reactions tend to be accelerated in an acidic environment because of the increased ionization of the electrolyte. While in an alkalic environment, when sodium, potassium, magnesium and calcium are present in a higher level, a coating isolating the metal substrate from the corrosive environment can be formed on metal surfaces as a protective layer, which is called a passive film. The rate of the corrosion reaction is therefore lower (Davis 2000).

2.6.2.2 Temperature effects

Composting is a self-heating process including both mesophilic and thermophilic phases to achieve organic waste stabilization (Haug 1993). In the thermophilic composting stage, the temperature is usually above 55°C and is maintained for one to three weeks or longer (depending on the composting system used). In view of corrosion which is an activation-controlled chemical reaction, the corrosion rate increases as more activation energy for electrochemical reactions is available in high temperatures (Davis 2000). Additionally, according to Nie et al. (2008), the passivation, which refers to the thin protective film formed on the surface of substrate metal, is maintained at low temperatures. However, as the temperature rises, the passive current density increases and the passive potential range decreases. This will lead to the breakdown of the protective film. Thus compost buried metal contaminants could be dominated by active dissolution when the thermophilic stage is reached.

2.6.2.3 Degree of aeration

Oxygen takes part in the cathodic reaction. Therefore, the oxygen level has a significant effect on the corrosion rate. A study conducted by Davis (2000) revealed that at any given temperature, there is a positive correlation between the corrosion rate of iron and the oxygen concentration. A high oxygen level indicates a condition which has a high oxidizing power. Therefore, there is a greater tendency to corrode or oxidize metals in contact with it. In the aerobic composting process, oxygen is maintained at a high level through continuing aeration, which provides an ideal condition for corrosion reactions.

2.6.2.4 Detrimental /beneficial species

In terms of detrimental/beneficial species, individual species even at trace levels can have a significant impact on corrosion behaviour. For example, according to Davis (2000), ammonia can greatly increase the corrosion of alloys because ammonia ions form soluble complexes with copper in the metal and the passive surface films break down. Chloride ions are harmful as they participate directly in anodic dissolution reaction and decrease the electrolyte resistivity. Sulphates are more benign in corrosive action towards metals; however, anaerobic sulphate-reducing bacteria can convert sulphate to sulphide which is highly corrosive (Ismail and EI-Shamy 2008).

2.6.2.5 Moisture

Corrosion can happen when about 70% humidity is present in the atmosphere (Ahmad 2006). Moisture represents the electrolyte required for electrochemical corrosion reactions and is therefore a prerequisite for the functioning of corrosion cells. In the composting process, the substrate moisture content is usually kept in a range of 50-70% to maintain a high microbial reaction rate (Haug 1993). In the enclosed composting facilities, when moisture is added up in the substrate mixture, the humidity around the contaminant also increases. Thus, the composting environment favours corrosion reactions.

2.6.2.6 Microbial activity

Microorganisms play an important role in the composting process, as well as in corrosion. For example, aerobic bacteria can oxidize iron or form mineral acids, and fungi may attack organic coatings formed on the surface of metals (Ismail and EI-Shamy, 2008). Sulphate-reducing bacteria (SRB), which are ubiquitous in anaerobic, sulphate-containing conditions, can catalyze the reduction of SO_4^{2-} to produce H_2S, which allows a corresponding corrosion of iron and steel. In addition, the acid-producing bacteria (e.g.

Thiobacillus) can also oxidize various sulphur-containing compounds to form sulphuric acid under aerobic condition, which can lead to the corrosion of metals (Davis, 2000).

2.7 Conclusion

A literature review on the contribution of different waste materials to the trace metal content in MSW revealed that batteries, ferrous, non-ferrous materials and electronic products are the main contributors. In view of the mixed MSW composting system, metals from these contributors can be released to the composting environment through pathways such as chemical reactions, physical abrasion and microbial transformation.

The composting environment is considered to be corrosive because of the high moisture, high temperature, various species and microorganisms, and aerobic conditions. Therefore, corrosion control is an important issue to the operators of indoor composting facilities. Basic corrosion theories were introduced. The models of the galvanic cell and concentration cell represent the general corrosion reactions that can lead to a metal loss from the contaminant to the composting environment. The corrosion weight loss method was proposed to quantify the metal mass transfer from the contaminant to the compost (organic fraction) during the composting process.

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CHAPTER 3 CONTAMINANT MASS TRANSFER DURING THERMOPHILIC COMPOSTING[1]

3.1 Introduction

The high level of trace metal content in compost is a concern when it comes to the compost quality. Literature review indicated that contaminants such as batteries, ferrous, non-ferrous materials and electronic products were the main contributors of trace metals in mixed municipal solid waste (MSW) (Rugg and Hanna 1992, Maystre and Viret 1993). With respect to the composting process using mixed MSW as the feedstock, how much metals would be transferred from these contaminants to the compost is critical information to evaluate their impact on compost quality.

The composting process provides a moist aerobic environment, which allows active and intensive biodegradation. It is also an optimal environment for corrosion to take place. During MSW composting, contaminants such as ferrous and non-ferrous materials may be exposed to a humid environment with the presence of various organic and inorganic species. Electrochemical reactions take place in nature in such an aqueous environment. Corrosion arises with the formation of anodic and cathodic areas on the contaminant's surface (Ahmad 2006).

In the interest of investigating the metal release from various contaminants, in this study, the corrosion concept was applied to quantify the metal mass transfer. The investigated metals were from the 11 trace elements listed in the Canadian Council of Ministers of the Environment (CCME) Guidelines for Compost Quality. The tested contaminants were mainly ferrous and non-ferrous materials since they could release trace metals to the composting environment through corrosion reactions. With respect to batteries and electrical products, which were also shown to be major contributors of trace metals in

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[1] *A version of this chapter has been accepted for publication. Zhou, McCartney, Chen, Yu and Abboud 2010. Proceedings of the 11th International Environmental Specialty Conference. Jun 9-12, 2010, Winnipeg, Manitoba.*

MSW, the corrosion concept is not applicable because of their physical characteristics. Therefore, they are excluded in this study and were tested in the next stage of experimentation when evaluating the impact of different contaminant on the trace metal content of compost.

During the composting process, factors such as aeration, relative degree of acidity or alkalinity, temperature, moisture, presence of detrimental / beneficial species and microbial activity can influence the corrosion behaviour (Davis 2000). According to Yu et al. (2008), a thermophilic composting process was carried out using a mixture of straw and alfalfa hay as the feedstock. The pH value of the composting substrate was much higher than the ones observed in MSW composting operations. With the hypothesis that the degree of acidity is the most critical factor in influencing the corrosion rate during the composting process, the experiment described in this study was carried out under similar conditions with two distinct pH ranges. Since high temperature is shown to accelerate the corrosion rate (Nie et al. 2008), this study only focused on the metal mass transfer during the thermophilic (>55^{o}C) composting stage. In order to understand the possible corrosion mechanism in a composting environment, the characterization of the composting substrate was carried out to investigate the presence of the corrosive species.

3.2 Experimental Design

3.2.1 Research Objectives

This research investigated the effect of a composting environment on the corrosion of typical metal contaminants found in the organic fraction of MSW. A synthetic feedstock, created to have a low potentially toxic element concentration, was used in the study. The resulting pH of this feedstock was higher than that typically found in the organic fraction of MSW (Yu et al. 2008), so a low pH feedstock was also created. The selected contaminants were exposed to the low pH (Lp) and high pH (Hp) feedstock for a three-week thermophilic composting process. The weight loss of each contaminant was determined using the corrosion weight loss method. The characterization of corrosion products and the corrosion condition was achieved by applying the Scanning Electron

Microscope (SEM-EDX), X-ray Diffractometer (XRD), Gas Chromatography (GC) and Ion-chromatography (IC) techniques. The result of the characterization helped to validate the corrosion method in determining metal contaminant mass transfer in the composting environment.

One hypothesis and three objectives guided the experiment:
(1) hypothesis: the low pH feedstock will result in higher contaminant weight loss due to corrosion as compared to the high pH feedstock;
(2) objective 1: to determine the metal mass transfer by quantifying the contaminant weight loss;
(3) objective 2: to evaluate the reliability of the corrosion method in determining the contaminant weight loss through specimen characterization;
(4) objective 3: to understand corrosion mechanisms by identifying the corrosion condition.

3.2.2 Methodology

3.2.2.1 Pilot-scale composting process

Apparatus

Two 1 m^3 drum composters (Transform Compost Systems Ltd., Abbotsford, BC, Canada) were used (Figure 3-1). Temperature probes (CCI Thermal Technologies Inc., Edmonton, Canada) located at depths of 20cm and 60cm from the bottom of each bioreactor were connected to a PC. With the probes remaining in the composting substrate during the experiment, LabVIEW 7.1 (National Instrument, USA) was used to monitor temperatures at one-hour intervals. A 1/50 hp aeration blower (BLWR AMU 75 with motor, Airdex Corp.) at the bottom of the bioreactor was also connected to the PC. Blowing frequency was controlled by LabVIEW 7.1. In this experiment, the frequency was set to blowing for one minute every 60 minutes during the first three days, and switched to blowing for 30 seconds every 120 minutes for the remainder of the experiment.

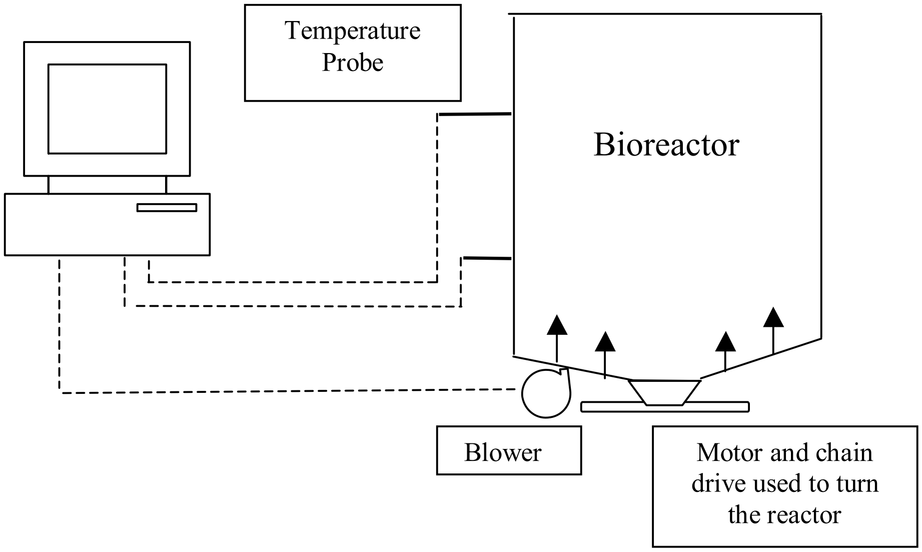


Figure 3-1 Bioreactor with temperature probes and blower connected to PC.

The bioreactors were equipped for leachate collection. Leachate could drip through the bottom of the reactor and was funnelled to a drainage port. A plastic bucket was used to collect the leachate.

Materials

Two feedstock mixtures with high and low pH levels respectively were used to conduct the composting process. Straw and alfalfa hay with a target total wet weight (ww) of 100kg were used as feedstock for both high pH (Hp) and low pH (Lp) treatments. The proportion of each feedstock material was calculated based on the C and N content to achieve a composting feedstock C:N ratio of 26:1. Physical and chemical properties of feedstock are presented in Table 3-1.

Peat moss (Alaska Peat Inc, Alberta Canada) and white sugar (Rogers, Canada), accounting for 25% and 5% (ww) of the feedstock, respectively, were added as amendments to maintain an acidic composting substrate in the Lp treatment (Hinton 2008). The peat moss was mixed with the feedstock materials at the beginning of the experiment, while the same amount of sugar was added at each turning. The characteristics of the peat and sugar are given in Table 3-2.

Table 3-1 Physical and chemical properties of synthetic feedstock material.

Material	Wet Weight[a] %	Dry Weight %	Moisture Content[b] %	C% (db)	N% (db)	C:N (db)	Bulk Density[c], Kg m^{-3} (wb)
Alfalfa hay	42.7	42.0	9.68	43.6	2.91	15.0	129.9
Straw	57.3	58.0	7.08	44.4	0.84	52.9	72.0
Feedstock	100.0	100.0	8.19	44.1	1.71	26	88.9

Notes: [a] The wet weight of each material was calculated based on the mean values of moisture content; [b] Standard deviation of moisture content was 0.81for alfalfa hay and 1.43 for straw; [c] standard deviation of bulk density was 1.5 for alfalfa hay and 0.8 for straw.

Table 3-2 Physical and chemical characteristics of peat moss and sugar.

	C:N	pH	Bulk Density (kg m^{-3}, wb)	Moisture Content (%)
Peat Moss	28.7	3.5	200.4	32.0
White Sugar	--	7.2	700.0	N/A[a]

Notes: [a] The moisture content for sugar was not tested because of its physical property.

The straw and alfalfa hay were size reduced to 10-15 cm long by using a 21 hp Riding Lawn Mower (John Deere, John Deere Engine by Briggs & Stratton). Peat moss and sugar were scattered evenly on the low pH treatment feedstock. All materials were mixed thoroughly by a stainless steel shovel to achieve good homogeneity. Since all the raw materials were air dried, water was added to reach 75% moisture content (ww). The feedstock recipes for each treatment are shown in Table 3-3.

Table 3-3 Weight of water and raw materials used in the experiment.

	Feedstock (kg, ww)		Amendment (kg, ww)		Water (kg)
	Straw	Alfalfa hay	Peat moss	White sugar	
Low pH	57.3	42.7	25.0	5.0	266.8
High pH	57.3	42.7	0	0	266.8

Process monitoring

During the 21 day composting process, samples were collected from both treatments to monitor changes in physical and chemical characteristics. All characterized parameters and analysing methods are given in Table 3-4.

Table 3-4 Summary of parameters and analysing methods for process monitoring.

Parameter	Equipment	Method
Bulk density	Scale (EB150FEG-1, Sartorius Ag Germany)	Measured in accordance with section 03.01-C Field Density, Free Airspace and Water-holding Capacity (TMECC 2001).
Height	--	Measured in-situ (accurate to1cm).
Moisture content	Isotemp Oven (Fisher Scientific)	Oven-drying at 70ºC for 24 h.
pH, electrical conductivity (EC)	Accumet® Multi-Meter (XL20, Fisher Scientific)	Determined in a suspension following the 1:5 slurry method described by section 04.10-A and 04.11-A (TMECC 2002).
Oxygen concentration	Oxygen metre (OT-21, Demista Instruments)	Tested in the central part of compost pile before turning.
NH_4-N, SO_4^{2-}, Cl^-, Mg^{2+}, Ca^{2+}	Ion-chromatograph with a PRP-X300 base-anion exchange column and cation exchange column.	In accordance with section 04.12-D Water-Soluble elements (TMECC 2002), compost samples were extracted prior to injection into IC column by: 1) centrifuge at 8000 *g* for 15 min; 2) filtered through 2µm filter.
Volatile fatty acids (acetic, propionic, isobutyric, butyric, isovaleric and valeric acid)	Gas chromatography with column: Stabilwax-DA 30 meter, 0.53mm ID, 0.5µm df (Restek Corp.).	Compost samples were extracted by adding diluted 25% phosphoric acid (4:1, v:v, deionised water:25%phosphoric acid), and then centrifuged at 8000 *g* for 15 min before injected into GC column.

Both reactors were turned at the same time every second day to achieve substrate mixing. Each turning was maintained for 10 minutes. The interior of the reactor was equipped with mixing paddles, which helped to mix the top and the bottom of the substrate. While the reactors were being turned, three samples from each (mass around 60g) were collected from different locations of the compost pile randomly. This random collection ensures that the whole substrate materials had equal opportunities to be tested.

Substrate bulk density was measured in accordance with TMECC Section 03.01-C Field Density, Free Airspace and Water-holding Capacity (TMECC 2001). The height of the compost pile and the oxygen concentration were measured in-situ before each turning event. To monitor the moisture content, pH and EC, the sample collection frequency was set to two days. Other parameters were monitored at a frequency of four days. The feedstock moisture, pH and EC were also tested right after its preparation. The turning and sampling time during the whole composting process are shown in Figure 3-2.

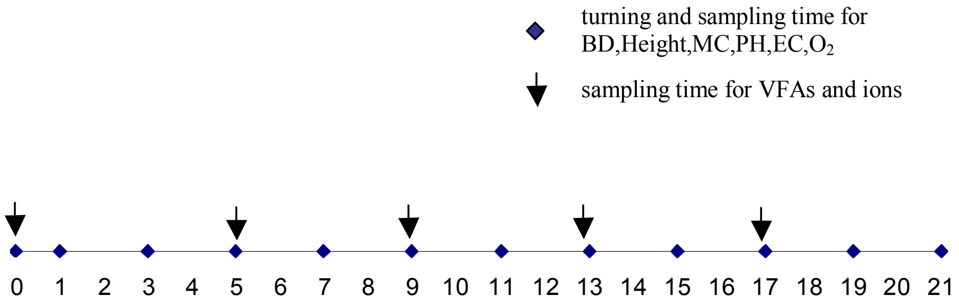


Figure 3-2 Turning and sampling frequency during the three-week composting process.

In order to minimize variations through sampling, each sample was chilled immediately upon collection (TMMEC 02.02, 2001). Each sample was placed into a Double Ziploc®-type 4-L (1-gal) bag and then placed in a cooler with ice. To reduce volatilization of organic compounds during storage, the airspace in each sample bag was minimized through pressing the bag by hand. All samples were sent to the laboratory and stored at 4°C for no more than 48h before analysis.

Experimental operation

The composting process lasted for 21 days, in accordance with the theoretical retention time in the high-rate composting phase of the City of Edmonton's Composting Facility (horizontal basin with lateral flow; Sorain Cecchini Tech, Italy). Time = 0 was set immediately after the feedstock was prepared and loaded into the bioreactor. The bioreactor operations were characterized as three distinct steps: start-up, routine operation and shut down.

(1) Start-up:

a) Weighed feedstock materials and mixed the materials while adding water;

b) Measured the feedstock bulk density in accordance with section 03.01-C Field Density, Free Airspace and Water-holding Capacity (TMECC 2001);

c) Collected three feedstock samples to test the moisture content, pH and EC. Samples were collected randomly from different locations to ensure that all materials have equal opportunities to be tested;

d) Removed temperature probes and placed the reactor in a vertical position to facilitate loading;
e) Switched on the reactor turning drive;
f) Loaded reactor with mixed feedstock using a conveyor (Univeyor Conveyors, Canada);
g) Stopped turning when loading was finished; replaced temperature probes and switched on the aeration blower;
h) Launched the control software, set temperature monitoring interval to one hour and the aeration cycle to blowing for one minute every 60 minutes;
i) Measured in-situ oxygen concentration and the height of feedstock;

(2) Routine operation:

Both reactors were turned every second day following the same steps:

a) Measured in-situ substrate oxygen concentration and height;
b) Removed temperature probes;
c) Tilted the reactor to facilitate sampling and amendment addition (Figure 3-3);
d) Turned the reactor for 10 minutes to mix the inside materials (Figure 3-4). While the reactor was being turned, collected three samples (mass around 60g) from different locations in the compost pile randomly; after collection, samples were placed into a Double Ziploc®-type 4-L (1-gal) bag and then placed in a cooler with ice.
e) Measured substrate bulk density in accordance with section 03.01-C Field Density, Free Airspace and Water-holding Capacity (TMECC 2001);
f) Distributed sugar into the substrate material in the Lp treatment using a shovel;
g) Determined substrate moisture, add water if the moisture is less than 75%;
h) Stopped turning after 10 minutes and return the reactor to the vertical position;
i) Replaced temperature probes;

Figure 3-3 Bioreactor after tilting.

Figure 3-4 Material mixing.

(3) Shut down:

a) Ended the process after 21 days;
b) Measured in-situ substrate bulk density, oxygen percent and height;
c) Removed temperature probes and switched off the aeration blower;
d) Closed monitoring software and collected temperature records;
e) Tilted the reactor to dump the reactor contents onto the floor;
f) Cleaned the reactor using high-pressure washer;
g) Disposed of final products in the appropriate place.

3.2.2.2Corrosion analyses for the contaminants

Apparatus

Analytical balance

The contaminant weight loss after 21 days in a thermophilic composting environment was measured gravimetrically using an analytical balance with an accuracy of 0.0001g (AB204-S/FACT, Mettler Toledo, Switzerland).

Scanning electron microscope and X-ray diffractometer

Corrosion products on the surface of each specimen were analyzed using a S-2700 Scanning Electron Microscope (SEM) with an Energy-Dispersive X-Ray Spectrometer (EDX) attachment, and a Rigaku Geigerflex 2173 X-ray diffractometer (XRD) with Co Kα incident radiation generated at 40kV and 30mA. A 2θ range of 2 to 120 degrees was adopted for the collection of X-rays.

Contaminants

According to the preliminary investigation on the Edmonton waste sort, nails, screws, scrap steel and wires were observed in the waste stream (Ge 2007). Thus, contaminants were selected from these categories. Galvanized nails and Zn-plated nails were selected since they both contain trace metal zinc on the base steel. Stainless steel flat washers were selected because of the chromium content. Copper wires and brass screws were selected because of the high copper content. The light bulb tail contains solders (consisting mainly of tin and lead) on the foot contact. Thus it was also tested in this study. The original contaminants were shown in Figure 3-5. The metal composition of each contaminant was determined through SEM-EDX analysis. The description of the physical and chemical properties of each contaminant is presented in Table 3-5.

Figure 3-5 Contaminants used in this experiment (from left: galvanized nail, Zn-plated screw, brass screw, copper wire, stainless steel flat washer, incandescent light bulb tail with separated Al-thread and foot contact).

Table 3-5 Physical and chemical properties of the selected ferrous and non-ferrous contaminants.

No.	Contaminant		Composition (Weight %)	Dimensions (mm)	Weight (g)
1	Galvanized nail	surface	Zn: 99.1 Fe: 0.9	ϕ 3.30 × 76.20	5.4741
		cross section	Fe: 99.0 Mn: 1.0		
2	Zn-plated screw	surface	Zn: 97.6 Fe: 2.0 Cr: 0.4	ϕ 2.90 × 63.50	3.9554
		cross section	Fe: 98.6 Mn: 1.4		
3	Stainless steel flat washers		Fe: 75.0 Cr:16.5 Ni: 8.5	ϕ 15.80 (outside) ϕ 7.13 (inside)	1.4046
4	Copper wire[a]		Cu:100	ϕ 2.00 × 25	0.7856
5	Brass screw		Cu: 64.1 Zn: 35.9	ϕ 3.90 × 50.80	4.2090
6	Light bulb tail (contact)		Sn: 98.7 Pb: 1.3	ϕ 10.00	0.3422

Note: [a] The copper wires were cut to 25 mm in length.

Specimen preparation

The test specimens were prepared in accordance with the Standard Test Method-Laboratory Corrosion Testing of Metals (NACE, 2000). To ensure that the contaminant weight change is significant, all contaminants were size reduced using an abrasive cutter (Abrasimet®2, Tech-Met, Canada). Only the shank (flat section) of the screw was used since the uniform surface is preferred for laboratory corrosion testing (NACE, 2000). The nails, screws and copper wires were cut to different lengths. Both ends of the section were then polished using a grinding machine (Metaserv 2000, Buehler Ltd., USA), labelled and coated with epoxy resin. The incandescent light bulb tail was separated into two parts: the aluminum-thread and the foot contact. Only the Pb-Sn alloy side of the foot contact was tested. The other side of the foot contact was coated with epoxy resin. In order to recover all the specimens from the compost efficiently at the end of the experiment, a bright-coloured fishing float (The Fishin'Hole, Canada) was attached to one end of each specimen as an indicator (Figure 3-6).

Figure 3-6 Specimens with indicator attached for the corrosion test (from left: galvanized nail, brass screw, Zn-plated screw, copper wire, stainless steel flat washer, light bulb tail foot contact).

Experimental procedures

For each treatment, twelve replications of each type of contaminant were prepared. All specimens were cleaned in alcohol for 30 minutes using an ultrasonic cleaner (S10H, Elma Ultrasonic Technology, Germany) to remove grease from the surface. Then they were weighed (accurate to 0.0001g) and attached with indicators. As the composting feedstock was loaded into the reactors, the specimens were distributed in the feedstock by hand.

At the end of the composting process, all specimens were recovered from the composting substrate using a metal detector (RD312, RJM Company), and then ultrasonically cleaned in acetone and air dried at room temperature. After the removal of surface contaminants and grease, the weight of each specimen was measured and recorded. A chemical cleaning was then applied using 5% acetic acid to remove corrosion products. After chemical cleaning, all specimens were weighed again. The results were used to calculate the weight loss.

Specimens of each contaminant were sent to the corrosion laboratory (Department of Chemical and Material Engineering, University of Alberta) for surface morphology analysis before and after being exposure to the composting environment (without chemical cleaning). SEM allowed the visual identification of surface structural features and EDX determined the chemical composition on the tested area.

3.3 Results and Discussion

3.3.1 Characteristics of the Composting Environment

3.3.1.1 Temperature

Temperatures at 60 cm and 20 cm from the bottom of the compost were monitored throughout the three-week process. Raw data is provided in Appendix A, Section A.1. Since that the height of the compost substrate in both reactors reduced constantly during the composting process, the temperature probes placed at 60 cm from the bottom of each reactor were partially exposed to the atmosphere. An underestimation of the real values may be caused. Thus, only the temperatures monitored at 20 cm from the bottom of the reactor were illustrated in Figure 3-7. Each value indicates the average temperature of every 24 hours.

In the Hp treatment, the temperature increased gradually to above 50ºC during the first week of composting and remained between 50ºC to 55ºC until the end of the process. In the Lp treatment, the temperature increased rapidly to reached the thermophilic (>55ºC) composting stage during the first three days, which indicated that the high rate microbial degradation was taking place. Thereafter, the temperature continued to increase to above 60ºC. Towards the end of the process, the values declined to around 55ºC, which indicated that the microbial degradation became moderate.

The higher temperatures in the Lp treatment suggested that the microbial degradation was more intensive than in the Hp treatment. This can be due to the continued addition of sugar, which provided a readily degradable carbon source to the microorganisms in the Lp treatment.

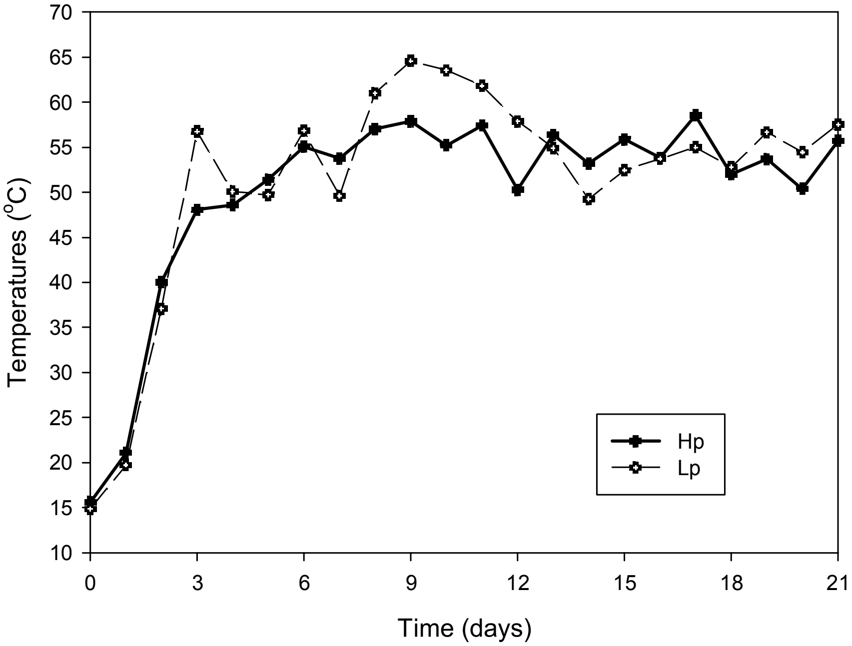


Figure 3-7 Temperature profiles in both treatments during 21 days of composting process.

3.3.1.2 pH and acids

The pH values in both treatments were monitored every second day. The raw data is given in Appendix A, Section A.2. In the Hp treatment, the composting substrate pH started from 7.8 and then increased steadily throughout the process (Figure 3-8). The end point pH was 8.9. The variations of pH values at each sampling point were lower than 0.2 units. In the Lp treatment, the initial pH was 7.4. It declined rapidly to 5.6 during the first three days and reached the minimum value of 4.6 on day 9. Thereafter, the pH slightly increased and remained between 4.8 and 5.4. The pH difference between the two treatments was 0.4-0.8 units during the first two days, while with the composting continued, the difference increased to 3.6-4.1 units. This suggested that acids were generated and accumulated during the composting process in the Lp treatment. Higher variations of pH values at each sampling point were observed. This may be due to the fact that the sugar added was not evenly distributed in the substrate materials. The variations can be reduced by extending the material mixing time.

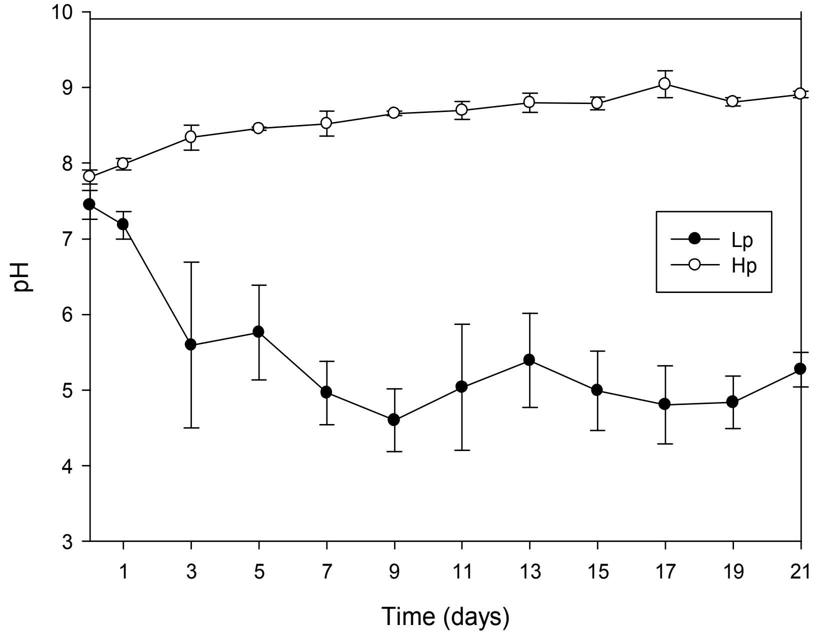


Figure 3-8 pH profile in Lp and Hp treatment during 21 days of composting. Each value is the mean of three replications ± 1 standard error of the mean.

The changes in the concentrations of total organic acids (acetic, propionic, isobutyric, butyric, isovaleric and valeric acid) during the composting process are illustrated in Figure 3-10. The raw data is provided in Appendix A, Section A.3. In the Lp treatment, the acid concentration increased remarkably from day 1 to day 9 and remained at a high level thereafter. In the Hp treatment, the acid concentration dropped rapidly from day 1 to day 5. Little changes were observed until the end of the process. The acetic acid was the dominant acid species in both treatments.

It can be noted that the acid concentrations in both treatments were clearly correlated to the pH values shown in Figure 3-8. During the period of pH declining in the Lp treatment, the concentration of total acids increased remarkably. This suggested that the continued addition of sugar into the composting substrate provided readily available organics, which can be rapidly decomposed and formed organic acids (Sundberg and Jönsson, 2005). In the Hp treatment, no sugar was added during the composting process, so organic acids were only generated at the beginning of the process. Thus, the pH remained high. It can be seen from the correlation between pH and acid concentrations that the pH control is effective in a pilot-scale composting experiment.

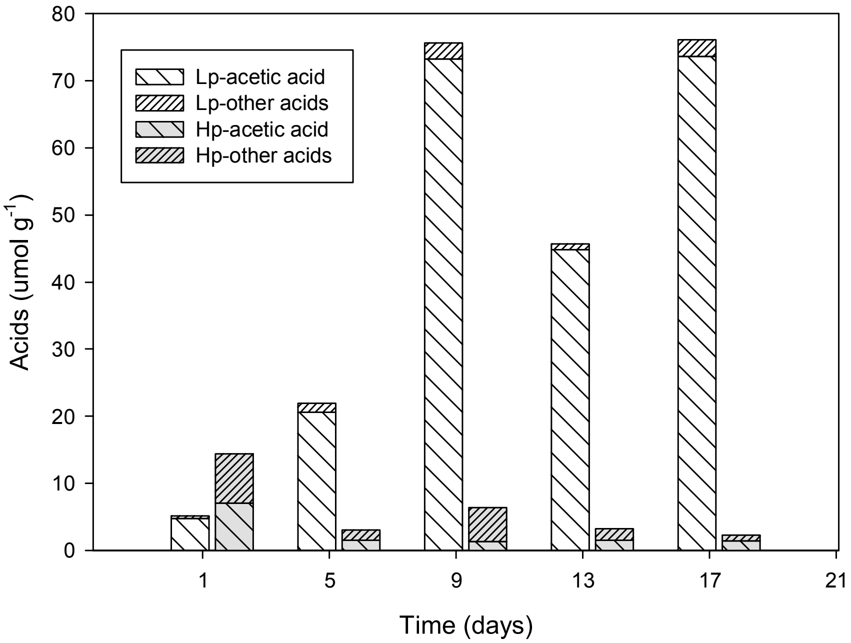


Figure 3-9 Total acids concentrations in both treatments during 21 days of composting. Other acids: propionic, isobutyric, butyric, isovaleric and valeric acid. Each value is the mean of two replicates.

3.3.1.3 Electrical conductivity (EC)

The raw data for EC values in both treatments is given in Appendix A, Section A.2. An increasing trend was shown in both treatments (Figure 3-10). The values in the Lp treatment were higher than the ones in the Hp treatment during the whole process. This suggested that more soluble ions were generated in the Lp treatment, which can be due to the intensive degradation reactions.

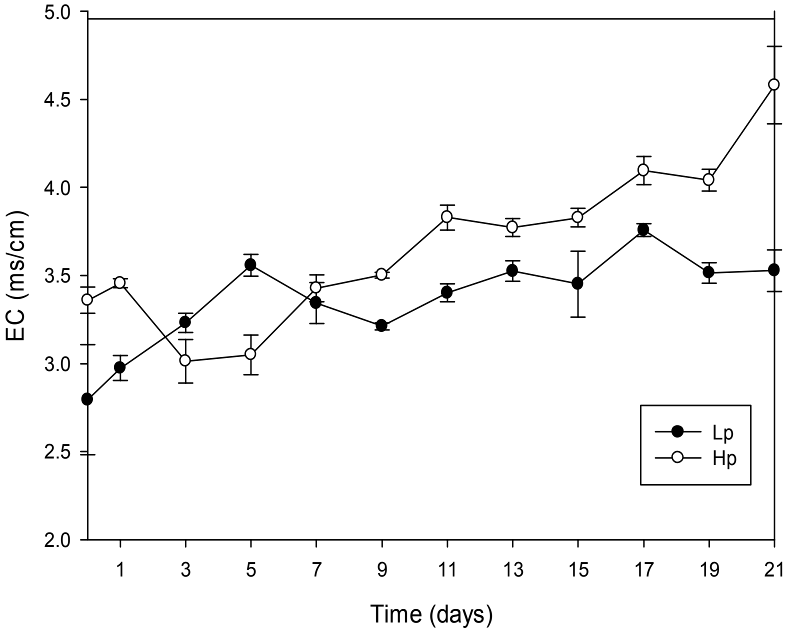


Figure 3-10 EC (ms cm^{-1}) profile in Lp and Hp treatment during 21 days of composting. Each value is the mean of three replications ± 1 standard error of the mean.

3.3.1.4 Ion concentration

Regarding the water soluble anions Cl^-, SO_4^{2-} and cations Ca^{2+}, Mg^{2+} contained in the composting environment, the difference in the initial ion concentration between the two treatments was relatively small (Appendix A, Section A.4). However, as the composting proceeded, distinct trends were observed in each treatment (Figure 3-11).

There was an increasing trend for chloride level in the Hp treatment, while the values in the Lp treatment were much lower and relatively constant. As tap water was routinely added into the compost substrate, the chloride ion contained in the water should result in an increasing concentration in both treatments. The low level of chloride in the Lp treatment might be due to the acidic environment: chloride ions could combine with metal ions present in the compost substrate to form undissociated complexes (Sawyer et al. 1994), thus removing the chloride ions from the solution.

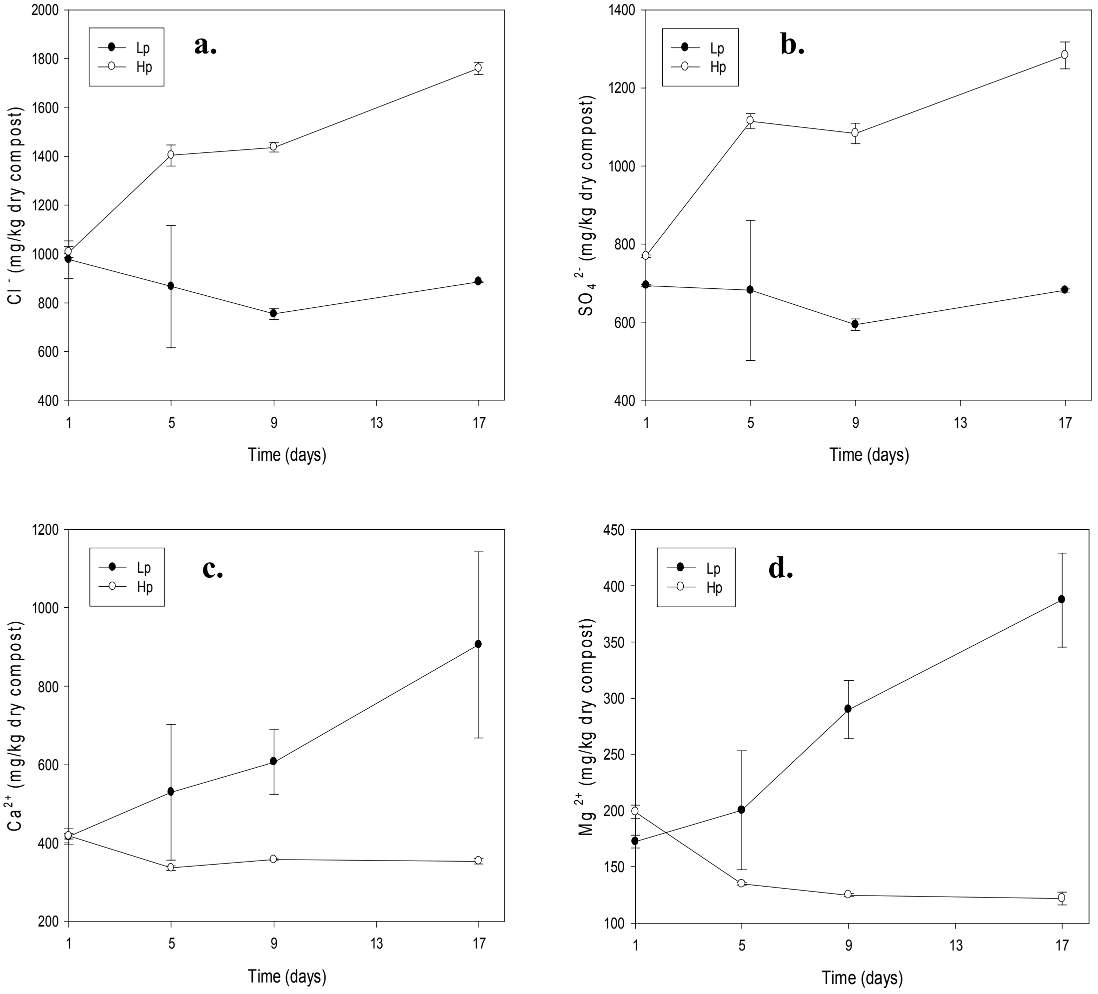


Figure 3-11 Water soluble ion concentration (mg kg^{-1} dry compost) profiles in both treatments during 21 days of composting. (a) Chloride (b) Sulphate (c) Calcium (d) Magnesium. Each value is the mean of two replications ± 1 standard error of the mean.

In regards to the sulphur cycle in a biodegradation system, the cumulative sulphate in the Hp treatment could be due to the sulphur mineralization and oxidation under aerobic conditions. While in the Lp treatment, the lower levels of sulphate could be due to two reasons: 1) the decomposition of organic sulphur in the compost substrate was limited by the continued addition of sugar, which was more readily decomposed; 2) in an acidic environment, sulphur is more likely to exist in a reduced form, as sulphide.

Since tap water was added into the composting substrate frequently during the experiment, an accumulation of Ca^{2+} and Mg^{2+} was observed in the Lp treatment. However, there was no accumulation in the Hp treatment. This may be due to the fact that in the Hp treatment, where the substrate pH was predominantly close to 9.0, both Ca^{2+} and Mg^{2+} were precipitated in forms of hydroxide or carbonate compounds. Since the pH and the system temperature remained at the same level in the Hp treatment, the changes in the amount of dissolved calcium and magnesium from day 5 to day 17 were less than 10%.

The correlation between the compost pH and the concentration of water-soluble cations and anions is shown in Figure 3-12. The concentration of anions appears higher when the pH increased, while the concentration of cations declined slightly. The latter observation may be caused by precipitation of the cations (Ca^{2+} and Mg^{2+}) in an alkalic condition. When the compost pH was around 5.0, no distinct trend was observed for the ion concentration. The differences between the concentrations of anions and cations was less in acidic as compared to alkalic conditions. All ions tend to be in the dissolved form when the substrate pH is low.

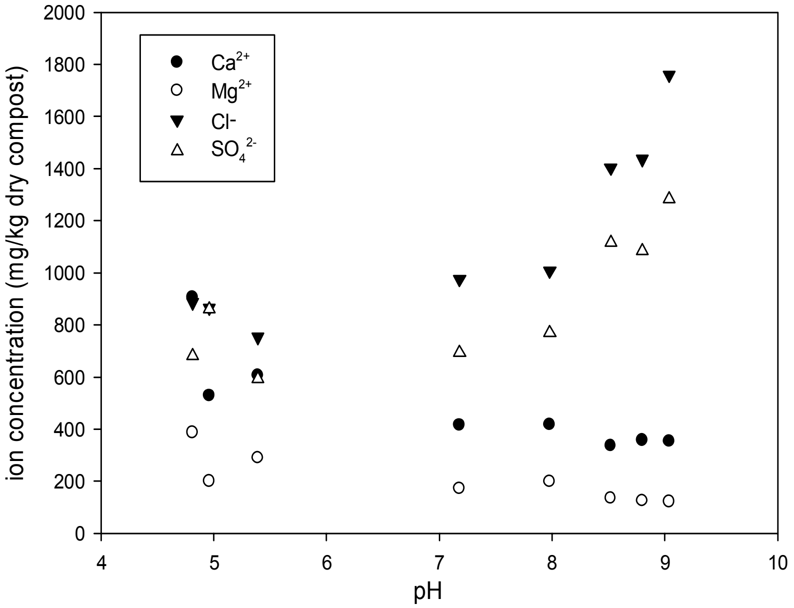


Figure 3-12 Correlation between ion concentration (mg kg^{-1} dry compos) and compost pH during the composting process.

Concerning the N-dynamics during composting, ammonium is converted from protein-N through ammonification (Insam et al. 2002). In the Hp treatment, the concentration of water soluble ammonium ions increased from 64.7 to 94.3 mg kg^{-1} (dry compost) from day 1 to day 5 (Figure 3-13). This may be due to the degradation of organic nitrogen through ammonification. Thereafter, the concentration of NH_4^+-N fluctuated within the range of 60 to100 mg kg^{-1} (dry compost). This might be caused by the shifting of the chemical equilibrium between NH_4^+ and NH_3.

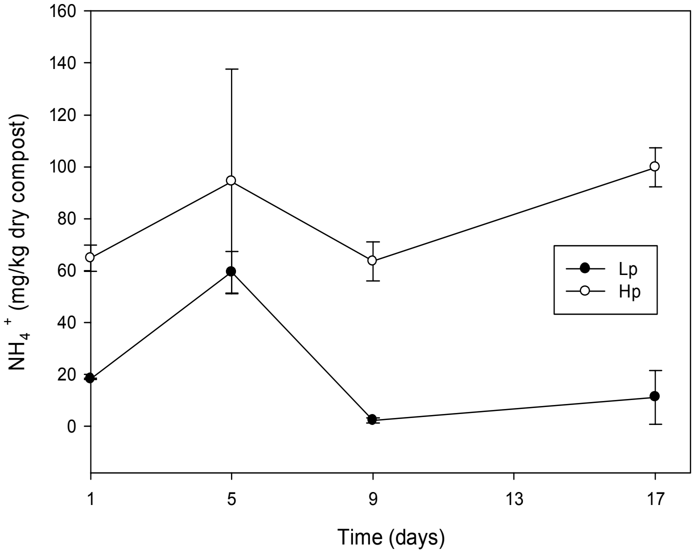


Figure 3-13 Water soluble ammonium ion concentration (mg kg^{-1} dry compost) profiles in both treatments during 21 days of composting. Each value is the mean of two replications ± 1 standard error of the mean.

The concentration of NH_4^+-N in the Lp treatment was lower than in the Hp treatment. This suggested that less organic nitrogen was decomposed in the Lp treatment than in the Hp treatment. Additionally, the concentration on day 17 (11.1 mg kg^{-1}, dry compost) was lower than the initial value (18.2 mg kg^{-1}, dry compost), which may be due to the loss of nitrogen in terms of ammonia gas (NH_3).

The current chemical analysis focused on calcium, magnesium, chloride, and sulphate. However, to further study the ion interactions under each specific pH condition, all major cations and anions should be analyzed. The additional parameters may include sodium and potassium as cation, and alkalinity, nitrate, and nitrite as anion.

3.3.2 Contaminant Corrosion Analyses

3.3.2.1 Weight loss measurement

A comparison of the specimen weight loss (after chemical cleaning) between the Lp and Hp treatments is shown in Figure 3-14. The raw data is presented in Appendix A, Section A.6.

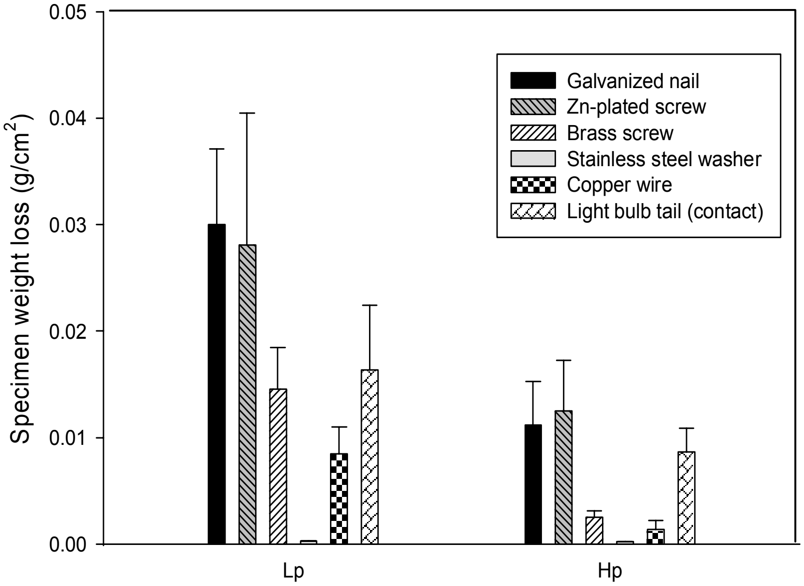


Figure 3-14 Specimen weight loss (g cm^{-2}) after 21 days of exposure to the composting environment (at 55-70°C) in Lp and Hp treatment. Each value is the mean ± 1 standard deviation of the mean.

In the Lp treatment, the galvanized nails and Zn-plated screws showed the highest weight losses, which were $(3.00\pm0.71)\times10^{-2}$ g cm^{-2} and $(2.81 \pm1.24)\times10^{-2}$ g cm^{-2} respectively. Since they both have zinc coating outside the steel surface, zinc was the primary trace metal released from the contaminant to the environment. The light bulb tails (contact), brass screws and copper wires showed moderate weight losses, which were approximately half the value of the galvanized nails. The stainless steel flat washers showed the lowest weight changes, which were two orders of magnitude lower than the other types of contaminants. This suggested that the stainless steel flat washers were hardly corroded during the composting process. According to the result, galvanized nails and Zn-plated screws raised the most concerns in terms of metal release during the composting process, while stainless steel flat washers raised the least.

In the Hp treatment, the weight losses of all the contaminants followed similar trends as was shown in the Lp treatment. All values were 1.5-7.5 times lower than those in the Lp treatment.

Results from the t-test ($\alpha=0.05$) suggested that the differences in the weight changes of each type of specimen between the two treatments were significant ($P < 0.05$) (Appendix C). All types of specimens showed higher weight losses in the Lp treatment than in Hp treatment, which suggested that the metal corrosion rate became higher in an acidic composting environment.

The metal mass transfer was calculated based on the specimen weight loss and the weight ratio of trace metal to the contaminant. Only the elements listed in the CCME Guidelines for Compost Quality were investigated and presented in Table 3-6.

Table 3-6 Summary of the trace metal mass transfer and the maximum disposal of each type of contaminant.

Contaminant	Trace Metal (weight ratio)	Specimen Weight Loss ($g\ cm^{-2}$)	Mass Transfer of Trace Metal ($g\ g^{-1}$)	Maximum Disposal[a] (g contaminant kg^{-1}compost, dw)
Galvanized nail	Zn (99%)	3.00×10^{-2}	Zn: 4.24×10^{-2}	16.50(3)
Zn-plated screw	Zn (98%)	2.81×10^{-2}	Zn: 5.52×10^{-2}	12.69(3)
Stainless steel flat washer	Cr (16.5%) Ni (8.6%)	2.95×10^{-4}	Cr: 2×10^{-4} Ni: 1×10^{-4}	547.35(390)
Copper wire	Cu (100%)	8×10^{-3}	Cu: 1.59×10^{-2}	25.12(32)
Brass screw	Cu (64.1%) Zn (35.9%)	1.46×10^{-2}	Cu: 1.91×10^{-2} Zn: 1.07×10^{-2}	20.99(5)
Light bulb tail (contact)	Pb (1.3%)	1.64×10^{-2}	Pb: 7.16×10^{-4}	209.50(765)

Note: [a] The value in the brackets indicates the number of each tested contaminant (before size reduction) needed to cause an exceedance.

The worse-case scenario specimen weight losses (after chemical cleaning) in the Lp treatment were used in the calculations. According to the maximum trace element content of the CCME category A compost (CCME 2005), the maximum disposal weight of each contaminant to one kilogram of compost (dry basis) was also calculated. For contaminants that contained two types of trace metal, the mass transfer values of both metals were used in the calculation of the contaminant maximum disposal. The lower value is presented in Table 3-6. A sample calculation is provided in Appendix F.

As summarized above, galvanized nails and Zn-plated screws showed the highest metal mass transfer among all the contaminants. In order to be in compliance with the CCME category A limit for zinc content in compost, a maximum of 16.50 g of the tested galvanized nails and 12.69 g of the tested Zn-plated screws could be disposed of in one kilogram of compost (dry basis). The mass transfer of copper from the brass screws was higher than from the copper wires. Looking at the light bulb tails (contact), the mass transfer of trace metal lead was low since it only accounts for 1.3% of the weight of the contaminant. The stainless steel flat washers showed a mass transfer which was two orders of magnitude lower than the other contaminants.

This study focused on the metal transfer during the thermophilic composting stage. However, corrosion could occur at the time that contaminants were disposed into the waste stream and the compost curing stage. The contaminant weight losses over the complete process may be underestimated. A future study is recommended on the investigation of contaminant metal transfer during the pre-composting stage and compost curing stage.

3.3.2.2 Specimen surface characterization

SEM micrographs (Figure 3-15, Figure 3-16) revealed the differences in specimen surface morphology before and after being exposed to the composting environment. Compared to the images taken after composting, a smooth and uniform surface image was observed on each original specimen. It was easy to notice the fractures and roughness on the surface metal, which suggested that the specimens are corroded during the composting process.

For the galvanized nails and Zn-plated screws in both treatments (Figure 3-15), the zinc coating was cracked and partially removed, leaving the internal steel exposed to the environment. This suggested that the zinc on the surface of the contaminant is available to react with the chemical species in the composting environment in terms of corrosion reactions.

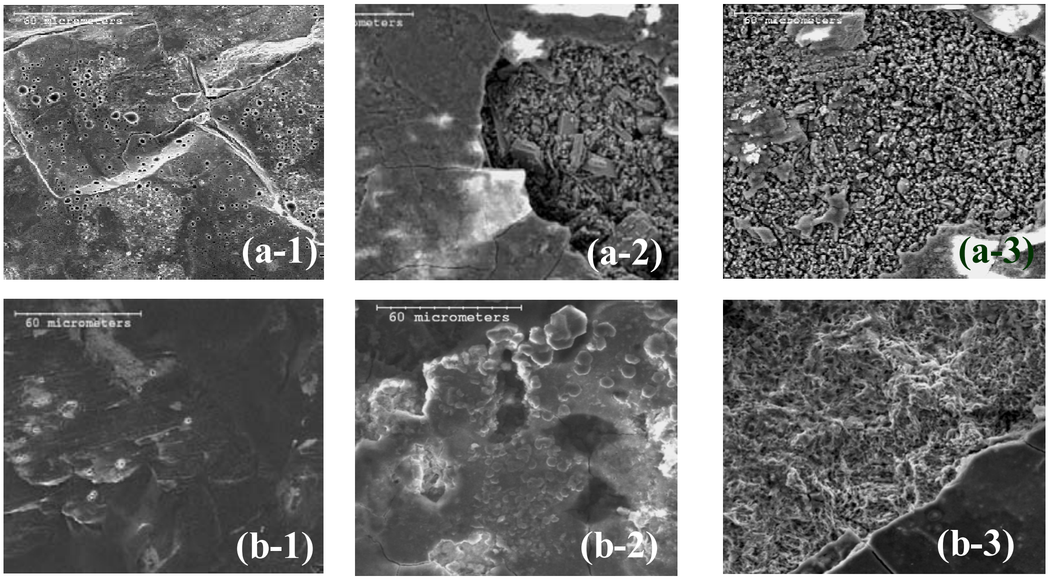


Figure 3-15 SEM micrographs of the tested specimen surface before and after 21 days of exposure to composting environment (at 55-70^{o}C) at a magnification of 60 µm: (a) Galvanized nail (b) Zn-plated screw. 1, 2 and 3 represent: before exposure to composting, exposed to Hp treatment, exposed to Lp treatment.

For copper wires, brass screws and light bulb tails (contact) (Figure 3-16), the specimens in the Lp treatment exhibited a rougher surface morphology. This suggested that the surface metal was potentially released to the environment and that a more severe corrosion took place in the Lp treatment than in the Hp treatment.

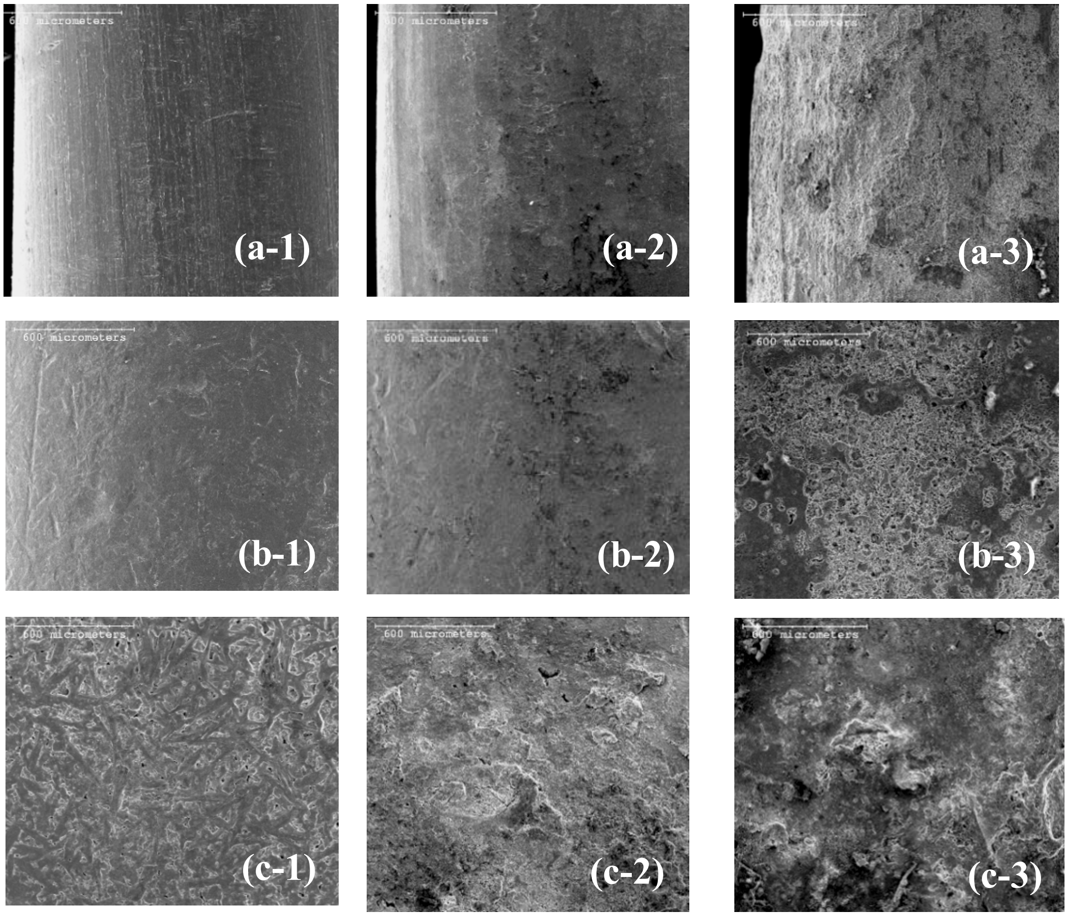


Figure 3-16 SEM micrographs of the tested specimens surface before and after 21 days of exposure to composting environment (at 55-70°C) at a magnification of 600 µm: (a) Copper wire (b) Brass screw (c) Light bulb tail (contact). 1, 2 and 3 represent: before exposure to composting, exposed to Hp treatment, exposed to Lp treatment.

EDX and XRD analyses were carried out to identify the elemental composition and corrosion compounds formed on each specimen's surface. Results from both analyses suggested that trace metals including zinc, copper, and lead were released to the composting environment during the 21-day experiment.

The EDX spectra for all specimens are shown in Figure 3-17. In addition to the metal elements from the tested specimen, non-metal species O, S, Cl, Si, P and metal species Ca, Mg were detected consistently in both treatments. No distinct difference in the chemical composition was observed between the two treatments, except that no zinc was detected on the surface of the Zn-plated screw in the Lp treatment after composting for 21 days. This could be due to the fact that the zinc coating reacted more severely in the Lp treatment than in Hp, thus more of the coating material was released into the composting environment. It is also worth noticing that in both treatments, lead was not shown on the spectra of the light bulb tail (contact). This suggested that the lead content was transferred to the environment during the composting process.

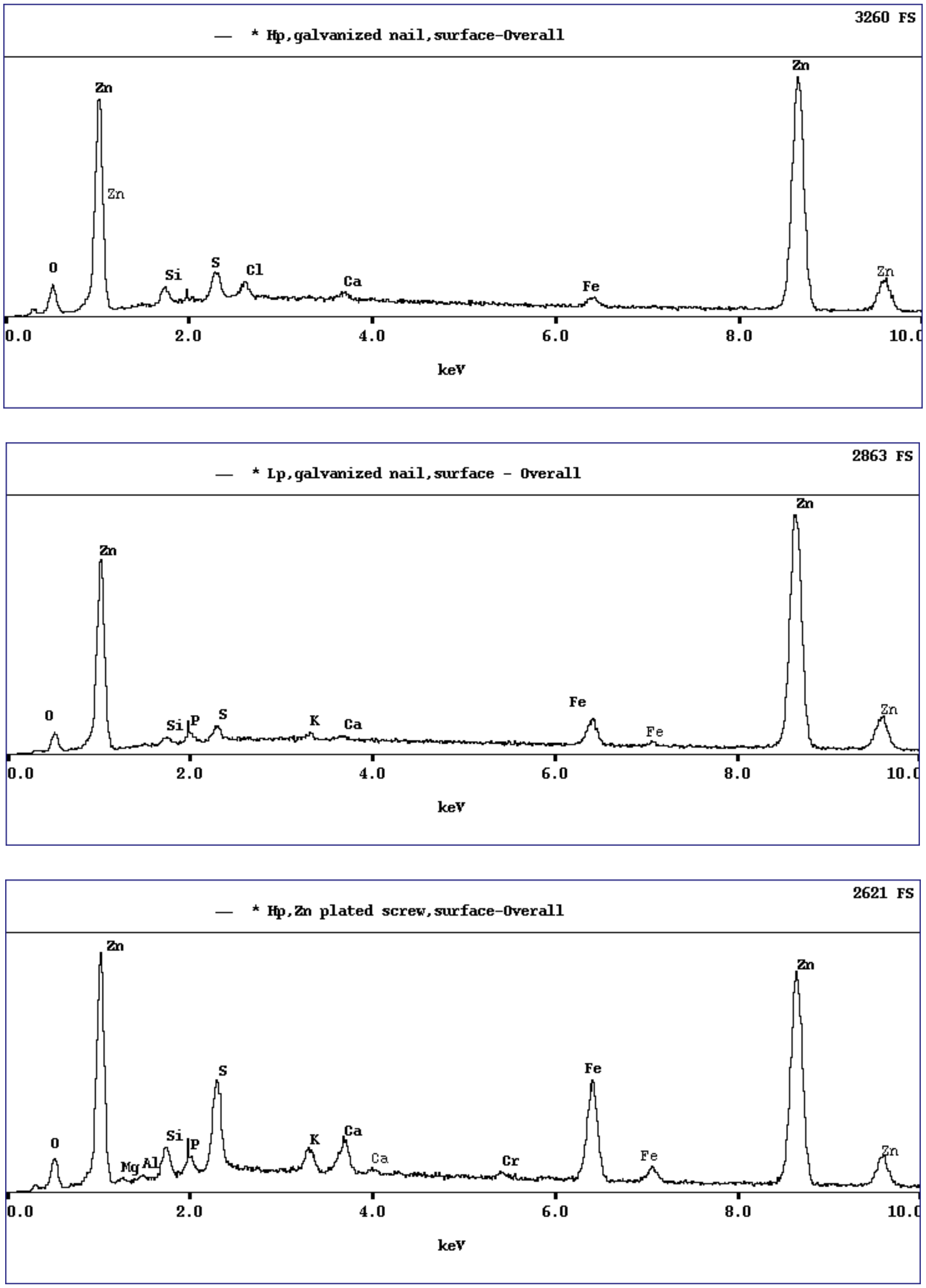
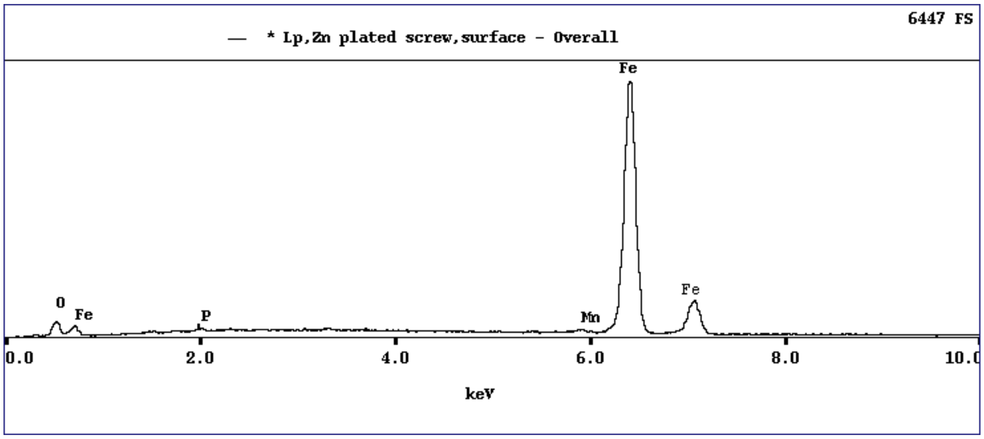
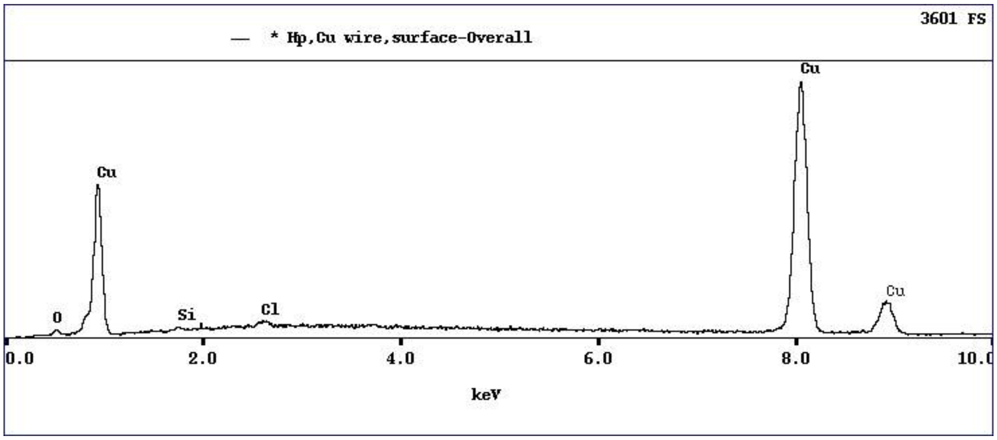


Figure 3-17 EDX spectra from the surface of all specimens in both treatments after being exposed to 21 days of a composting environment at 55-70°C.





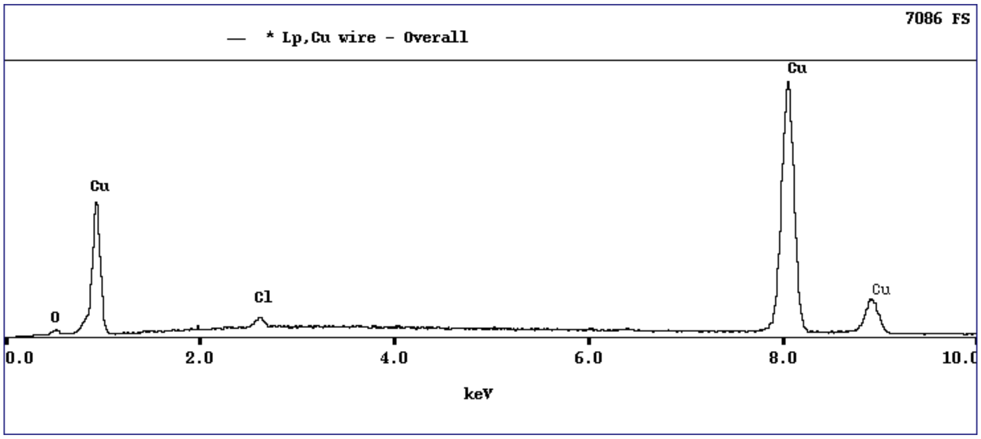


Figure 3-17 (continued) EDX spectra from the surface of all specimens in both treatments after being exposed to 21 days of a composting environment at 55-70°C.

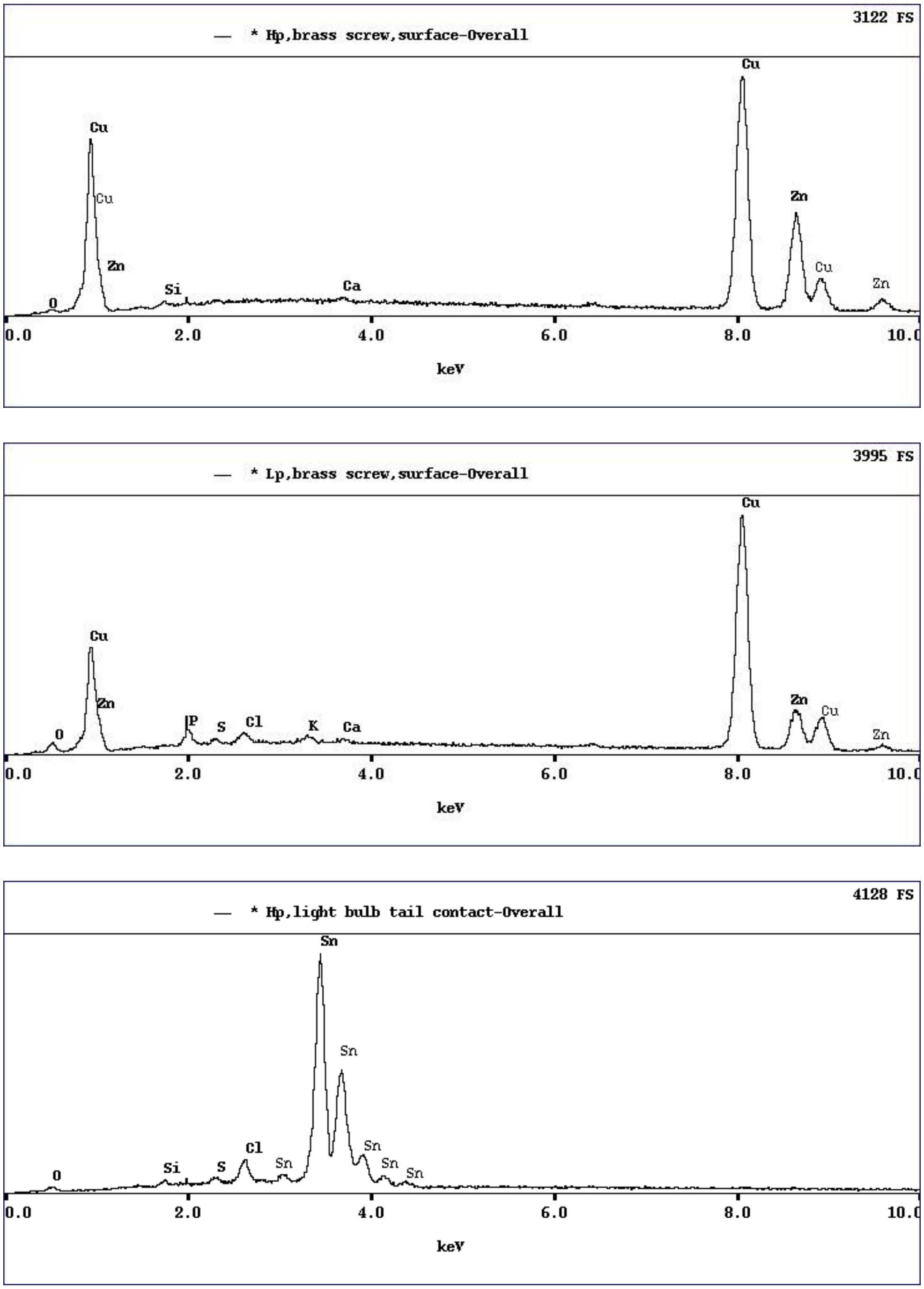
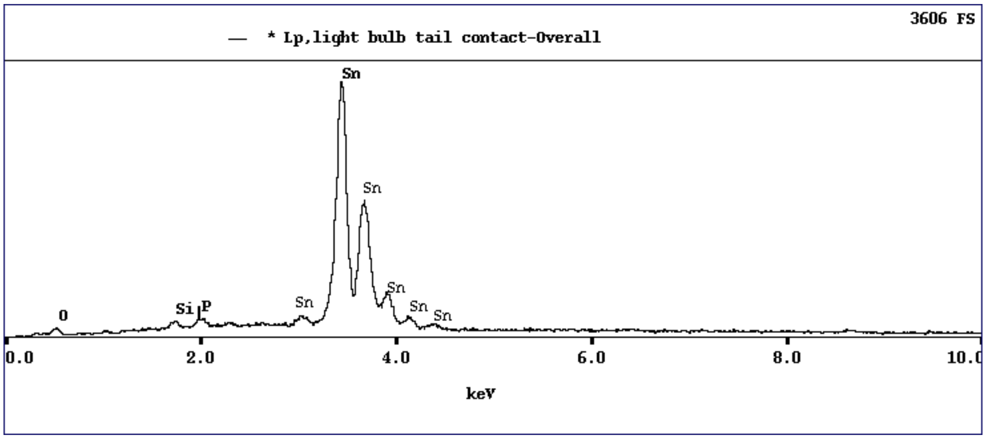
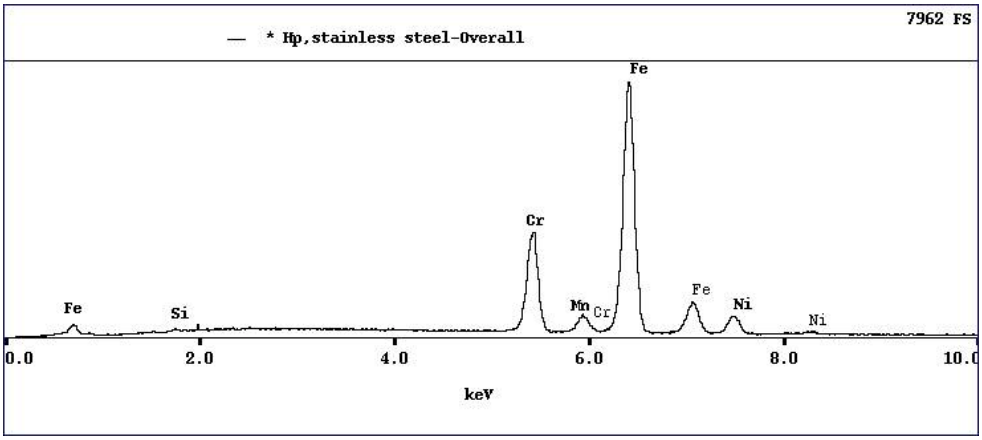


Figure 3-17 (continued) EDX spectra from the surface of all specimens in both treatments after being exposed to 21 days of a composting environment at 55-70°C.





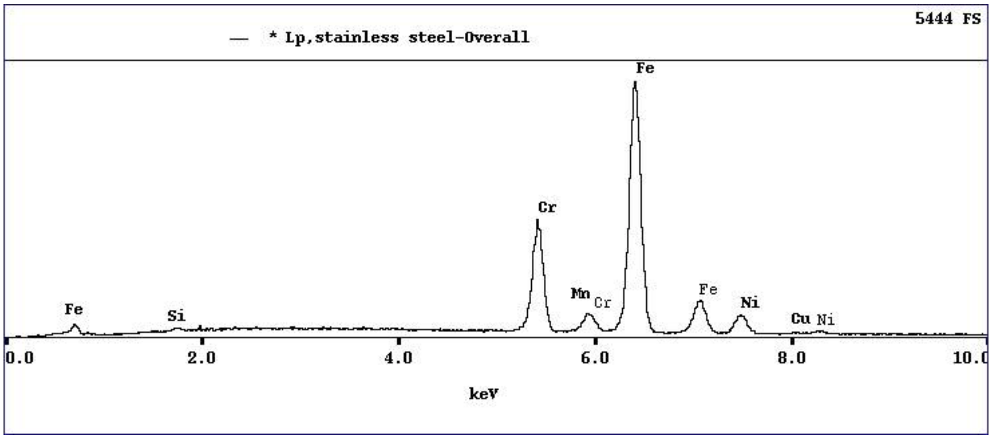


Figure 3-17 (continued) EDX spectra from the surface of all specimens in both treatments after being exposed to 21 days of a composting environment at 55-70°C.

The chemical analysis with XRD identified the composition of the corrosion products formed after composting (Table 3-7). For both the galvanized nail and Zn-plated screw, zinc was coated on the surface of the steel. Since zinc has a lower standard potential than iron (E^0_{Zn}= -0.763, E^0_{Fe}= -0.440), it could act as an anode to protect the base metal of steel from being corroded ($Zn \rightarrow Zn^{2+} + 2e^-$) (Perez, 2004). Thus the zinc layer would break down first under corrosive conditions. From the result of the XRD test, no zinc was detected on the Zn-plated screw in the Lp treatment. This suggested that the zinc coating was released to the environment.

Chlorine, oxygen and sulphur were found to be associated with copper and iron on the surface of galvanized nails, Zn-plated screws, copper wires and brass screws. This indicated that the metal contaminants were corroded by the detrimental species such as Cl^-, OH^- and SO_4^{2-} in a composting environment.

Table 3-7 XRD results of specimens in both treatments after exposed to 21 days composting at 55-70°C.

No.	Specimen	Chemical compounds detected	
		Hp treatment	**Lp treatment**
1	Galvanized nail	$FeZn_{13}$	Zn, Fe_2O_3, $FeZn_{13}$
2	Zn-plated screw	$Cr_{0.045}Fe_{0.955}S$, $Fe_{12}S_{11}O_{51}$	Fe
3	Copper wire	Cu, Cu_9Si, Cu_4O_3	Cu, Cu_2O
4	Brass screw	Cu_3Zn, CuZn	CuO, $CuCl_2$, Cu_2O, $Cu_{0.7}Zn_{0.3}$, SiO_2
5	Light bulb tail (contact)	Sn, Fe, Fe_2SiS_4, $Mn_{+2}O$	SiO_2
6	Stainless steel flat washer	Fe_2Si	Fe_3Si

The corrosion products detected by XRD demonstrated the release of trace metals from the contaminant to the environment through the corrosion reaction. However, due to the fact that XRD can only detect compounds that have a weight ratio above 5%, there could be more corrosion products on the specimen surfaces that were not identified.

3.4 Summary and Conclusions

In order to investigate the trace metal mass transfer from various contaminants during the thermophilc composting process, six types of ferrous and non-ferrous contaminants were tested in two composting treatments. The composting conditions (feedstock materials, aeration and temperature) remained the same in both treatments except a low pH (Lp) treatment (with the addition of the amendment) showed a acidic substrate (the pH ranged from 4.6 to 7.4), and a high pH (Hp) treatment (without any addition of the amendment) showed an alkalic substrate (the pH ranged from 7.8 to 8.9). A higher concentration of total organic acids was shown in the Lp treatment, which suggested that the continued addition of the amendment sugar was effective in maintaining an acidic composting environment by generating organic acids.

Every type of contaminant showed a higher weight loss in the Lp treatment than in the Hp treatment, which suggested that the corrosion rate was accelerated by the acidic composting environment. Considering the worst-case scenario, only the weight loss in the Lp treatment were discussed in this study. Comparing the weight losses of the contaminants in the Lp treatment, the galvanized nails and Zn-plated screws showed the highest values, while the stainless steel flat washers showed the lowest. The high mass transfer of zinc from the galvanized nails and Zn-plated screws suggested that they might be the main contributors to the zinc content in the composts. In order to reach the CCME category A compost quality, the maximum disposal of the tested galvanized nails and Zn-plated screws in one kilogram of compost (dry basis) is 16.50 g and 12.69 g, respectively. The mass transfers of copper from brass screws and copper wires were moderate; the maximum disposal mass to one kilogram of compost (dry basis) is 20.99 g and 25.12 g, respectively. Very little trace metal was transferred from the stainless steel flat washers and light bulb tails (contact). Thus, they are not the main contributors of the trace metal content in composts.

The specimen surface characterization with SEM-EDX and XRD analysis revealed that species such as chloride, hydroxyl and sulphate existing in the composting substrate reacted with the metals on the contaminant's surface and formed corresponding corrosion products. The corrosion weight loss measurement is reliable in determining the trace metal mass transfer from various contaminants during the composting process.

It was assumed that the corrosion rate was accelerated by the high temperature and intensive microbial activity; therefore, this study only focused on the contaminant metal transfer during the thermophilic composting stage. However, this assumption may lead to an underestimation of the actual metal transfer. The corrosion may also occur during the material mixing and compost curing stages. A further study is recommended to investigate the contaminant metal transfer before and after the thermophilic stage.

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CHAPTER 4 THE IMPACT OF DIFFERENT CONTAMINANTS ON THE TRACE METAL CONTENT OF COMPOST

4.1 Introduction

4.1.1 Background

The municipal solid waste (MSW) composting feedstock contains contaminants such as plastics, glass, wood products and metals that may come from disposed household wastes. These contaminants may result in the presence of high levels of trace elements, often referred to as trace metals, in the compost product (Epstein et al 1992; Woodbury and Breslin 1992). The trace elements are potentially toxic to humans and tend to accumulate in soils with long term application. To protect the public health and the environment, the Canadian Food Inspection Agency (CFIA) established standards for the acceptable maximums of metal concentration in compost and the acceptable maximums of cumulative metal additions to soil (CFIA 1997). The Canadian Council of Ministers of the Environment (CCME) also proposed limits on the trace element content in the compost and classified the compost products into two grades (Category A – unrestricted and Category B – restricted) based on the compost quality (CCME 2005).

The Edmonton Composting Facility (ECF) processes mixed MSW as composting feedstock. The ECF compost product meets the CCME Category B criteria. Five trace elements in the compost product: zinc, copper, nickel, molybdenum and selenium, have prevented the ECF from achieving a Category A designation (City of Edmonton 2009). In order to apply the ECF composts to the unrestricted use, it is necessary to reduce the levels of these trace elements.

Batteries, ferrous, non-ferrous materials and electronic products disposed of in the waste stream are the main contributors of trace metals in MSW (Rugg and Hanna 1992, Maystre and Viret 1993). However, whether these contaminants could be the contributors of the high trace metal content in the compost product is still unknown. Therefore, evaluating the impact of these contaminants on the high trace metal content of compost was the focus of this study.

4.1.2 Contaminant Selection Criteria

Studies (Rugg and Hanna 1992; Maystre and Viret 1993) have revealed that non-compostable wastes such as batteries, ferrous, non-ferrous materials and electronic products are the main contributors of heavy metals in the municipal solid waste stream. They could release trace metals into the compost substrate during the composting process which would lead to the elevated metal content in the compost product. This study was conducted to investigate whether the released metals would result in an increase of the trace metal content in the compost (organic fraction). Two criteria guided the contaminant selection in this study:

(1) the contribution of each contaminant to the trace metal content in MSW; and
(2) the physical characteristics (i.quality; ii.surface area to mass ratio; iii. protective covering).

Batteries were reported to have the highest contribution to the trace metals in MSW (Ge 2007). Alkaline batteries are the most commonly used household batteries (Ge 2005). As reported by Jennings (2004), batteries which are not labelled by manufacturers or are poorly constructed with zinc barrels tend to have a high leakage rate under hostile environmental condition. They are referred to as low quality batteries in this study. Batteries which are properly labelled by manufacturers and are constructed with steel barrels are less likely to release any pollutant. They are referred to as high quality batteries and tested alongside the low quality ones in this study. The effect of the contaminant's quality on the metal content of compost was evaluated based on the comparison of the results from these two types of batteries.

Ferrous and non-ferrous materials also contribute high levels of trace metals in MSW (Ge 2007). The study on quantifying trace metal mass transfer, reported in Chapter 3, was conducted from the standpoint of contaminant weight loss due to corrosion during the composting process. The results showed that under the experimental composting conditions, the tested ferrous and non-ferrous contaminants released zinc, copper, nickel, lead and chromium to the composting environment. The metal transfers from each tested contaminant are presented in Table 4-1.

Table 4-1 Trace metal mass transfer from ferrous and non-ferrous metals (Adapted from Table 3-6, Chapter 3).

Category	Contaminant	Mass Transfer of Trace Metal ($g\ g^{-1}$)
Ferrous metals	Galvanized nail	Zn: 4.24×10^{-2}
	Zn-plated screw	Zn: 5.52×10^{-2}
	Stainless steel flat washer	Cr: 2×10^{-4} Ni: 1×10^{-4}
Non-ferrous metals	Copper wire	Cu: 1.59×10^{-2}
	Brass screw	Cu: 1.91×10^{-2} Zn: 1.07×10^{-2}
	Light bulb tail (contact)	Pb: 7.16×10^{-4}

From the category of ferrous metals, galvanized nails and Zn-plated screws were tested in this study. According to the metal mass transfer during the composting process, the galvanized nails and the Zn-plated screws released 4.24×10^{-2} g g^{-1} and 5.52×10^{-2} g g^{-1} of zinc, respectively (Table 4-1). No stainless steel material was tested because of the very low metal mass transfer. Since the screws have a higher surface area to mass ratio than the same weight in nails, the impact of surface area to mass ratio on the increase in compost trace metal content was evaluated.

In the category of non-ferrous materials, copper wires, which released 1.59×10^{-2} g g^{-1} copper, were tested in this study. Electronic cables were selected from the category of electronic products, which is reported as another contributor of trace metals in MSW (Ge 2007). Since the only difference between electronic cables and copper wires is the plastic sheath outside the copper core of the cable, the effect of protective covering on the metal content of compost was assessed.

4.2 Experimental Design

4.2.1 Objectives

This study was carried out to assess the impact of various contaminants on the compost trace metal content. A synthetic composting feedstock with low potentially toxic element (PTE) concentrations was used in this study. Peat moss and sugar were added as amendments to maintain an acidic composting condition. The selected contaminants were exposed to a thermophilic composting process for three weeks. This study aimed to:

1) determine the increase in the trace metal content in the compost product;
2) evaluate the impact of each contaminant on the compost trace metal content;
3) assess the effect of contaminant characteristics including quality, surface to mass ratio, and protective covering on the increase in the trace metal content in the compost product.

4.2.2 Materials

4.2.2.1 Apparatus

Seven 1 m^3 drum composters (Transform Compost Systems Ltd., Abbotsford, BC, Canada) were used to carry out the composting process (the same as were illustrated in Figure 3-1, Chapter 3). Each bioreactor was equipped with two temperature probes (CCI Thermal Technologies Inc., Edmonton, Canada), which were located at heights of 20cm and 60cm from the bottom of the bioreactor. A 1/50 hp aeration blower (BLWR AMU 75 with motor, Airdex Corp.) was also installed to provide upward aeration. LabVIEW 7.1 (National Instruments, USA) was used to monitor the temperature at one-hour intervals and to control the blowing frequency. In this experiment, the frequency was set to blowing for 60 seconds every 60 minutes during the first three days, and then switched to blow for 30 seconds every 120 minutes for the remainder of the experiment. Leachate could drip through the bottom of the reactor and was collected by a plastic bucket.

4.2.2.2 Feedstock material

The composition of the feedstock mixture, the physical and chemical properties of each feedstock material were the same as illustrated in Table 3-1, Chapter 3. The total weight of the feedstock mixture was 100kg (ww). Peat moss (Alaska Peat Inc, Alberta Canada) and white sugar (Rogers, Canada), accounting for 25% and 5% (ww) of the feedstock, respectively, were scattered evenly onto the feedstock as amendment (Hinton 2008).

All feedstock materials were size reduced to a length of 10-15 cm by using a Riding Lawn Mower (John Deere, 21 horse power Briggs & Stratton engine) and then mixed thoroughly to achieve good homogeneity. Stainless steel shovels were used in order to minimize the metal contamination from the tools during the mixing of the materials. Since all the raw materials were air dried, water was added to reach 70% moisture content. The feedstock recipe for each treatment is shown in Table 4-2.

Table 4-2 Mass (kg, ww) of water and raw materials used in the experiment.

	Feedstock		**Amendment**		**Water**
	Straw	**Alfalfa hay**	**Peat moss**	**White sugar**	
Mass (kg, ww)	57.3	42.7	25.0	5.0	266.8

The results for metal analysis for feedstock materials and the peat moss are summarized in Table 4-3. The estimated metal content of the feedstock mixture is also provided. The raw data is given in Appendix B, Section B.5. All trace metal contents are less than 20% of the CCME category A limit except molybdenum and zinc, due to the high concentrations in the alfalfa hay.

Table 4-3 Metal concentrations (mg kg^{-1} dry weight), standard deviations (SD) for feedstock materials and peat moss (number of samples = 2).

	Alfalfa hay Mean (SD)	**Straw Mean (SD)**	**Peat Moss Mean (SD)**	**Feedstock Mixture**	**CCME Category A Limit**	**Feedstock / CCME A Limit (%)**
As	0.69 (0.44)	0.08 (0.01)	1.30 (0.03)	0.48	13	4
Cd	0.13 (0.01)	0.15 (0.01)	0.16 (0.01)	0.15	3	5
Co	0.84 (0.43)	0.16 (0.07)	1.22 (0.08)	0.57	34	2
Cr	6.33 (3.25)	4.34 (0.71)	2.90 (0.25)	4.82	210	2
Cu	10.64 (1.37)	5.91 (0.52)	4.02 (0.07)	7.29	400	2
Hg	0.05 (0.03)	0.03 (0.00)	0.05 (0.00)	0.04	0.8	5
Mo	4.74 (0.45)	0.54 (0.05)	0.67 (0.01)	2.05	5	41
Ni	4.23 (1.33)	1.96 (0.17)	2.26 (0.06)	2.81	62	5
Pb	2.09 (0.48)	0.75 (0.20)	1.64 (0.07)	1.37	150	1
Se	0.39 (0.03)	0.10 (0.00)	0.45 (0.01)	0.26	2	13
Zn	296.63 (75.12)	13.09 (0.46)	26.26 (0.23)	115.65	700	17

4.2.2.3 Selected contaminants

In total, six types of contaminants from the categories of batteries, ferrous, non-ferrous materials and electronic products were tested in this experiment. The description of each contaminant is summarized in Table 4-4.

Table 4-4 Description of the contaminant tested in the experiment.

No.	Contaminant	Characteristics	Source
1	High Quality AA Alkaline Batteries	Well constructed with steel barrels.	Home Depot
2	Low Quality AA Alkaline Batteries	Poorly constructed with zinc barrels.	Dollar Store
3	Galvanized Nails	Φ3.30×76.2mm; bare carbon steel with Zn coating;	Home Depot (Tree Island Industries Ltd. Richmond, BC, Canada)
4	Zn-plated Screws	Φ2.90×63.50mm; bare carbon steel with Zn coating;	Rona (H.Paulin& Co.Limited, Toronto Canada)
5	Copper Wires	Φ2.00 mm, 40 cm in length; bare copper;	Home Depot (imported by Grabber Construction Products)
6	Electronic Cables	Φ 5 mm, 40 cm in length; copper core in tight sheath	Home Depot

4.2.3 Methods

4.2.3.1 Amount of contaminant added

Regarding the amount of contaminant added, two factors should be taken into consideration: 1) the metal release from the contaminant; and 2) the metal concentration in the feedstock mixture.

In view of metal release, contaminants (including galvanized nails, Zn-plated screws and copper wires) had known metal transfers under the experimental composting condition from the results reported in Chapter 3, which were 0.0424 g g^{-1}, 0.0552 g g^{-1} and 0.0159 g g^{-1} (Table 4-3). Electronic cables were assumed to have the same metal transfer as copper wires. As the values for batteries were unknown, an assumption of a 0.01 (g g^{-1} battery) metal transfer was made.

The feedstock metal content also has an impact on the detection of the metal increase resulting from the contaminants. If the metal released from the contaminant is less than the metal content in the feedstock material, no significant metal increase could be detected. Therefore, each type of contaminant was added in sufficient amounts to ensure a metal increase in the compost substrate is higher than the maximum standard deviation of feedstock materials. Additionally, in order to avoid the inhibition of the composting process by excessive amounts of contaminant, the volume of each type of contaminant was less than 2% of the total feedstock volume. Combining the two factors discussed above the procedures for the determination of the amount of contaminant added into each treatment is illustrated in Figure 4-1 (Ge 2007).

The weight percentage of each type of contaminant was determined based on City of Edmonton's waste sort result (Appendix E). The wastes were collected from both single family and multi-family (such as apartment buildings, row houses, condominium complexes, etc.) from areas throughout the entire City. The waste sort samples were taken and analysed after they were delivered to the tipping floor, which represent as received compost feedstock material (City of Edmonton 2003).

Assuming that 100kg of feedstock (ww) was used, the total mass of the contaminants was calculated. The composting substrate mass reduction after composting was assumed to be 50%. With the known metal transfer, the increase in metal content of compost was then estimated. To illustrate the procedures, an example for copper wire is given as follows:

1. According to Edmonton's waste sort (Appendix E), combining the category of mixed metal & materials and other, set 1.22% (weight percentage) of copper wires to be added into the feedstock;
2. The mass of copper wires added into 100kg feedstock is 1220 g;
3. The mass of Cu transferred: 1220 g × 100% (Cu) × 1.59% (transfer) = 19.43g;
4. The increase in Cu concentration in the compost (assuming 50% mass reduction): 19.43 g / (100 kg ×50%) = 388.55 mg kg^{-1} dry weight;
5. The maximum standard deviation of Cu concentration in the feedstock: 1.37 mg kg^{-1} (Table 4-6), increase in Cu concentration > maximum standard deviation;
6. The mass of 40 cm copper wire is 12.57g, pieces of 40 cm copper wire is: 1220g/12.57g = 97; the volume of 40 cm copper wire is 0.001L, the volume of copper wires is: 0.001L×97 = 0.097L; the volume percentage of copper wires is 0.097L / 1101.32L (feedstock) = 0.008% < 2%;

7. The proposed 1220g of copper wires added is sufficient.

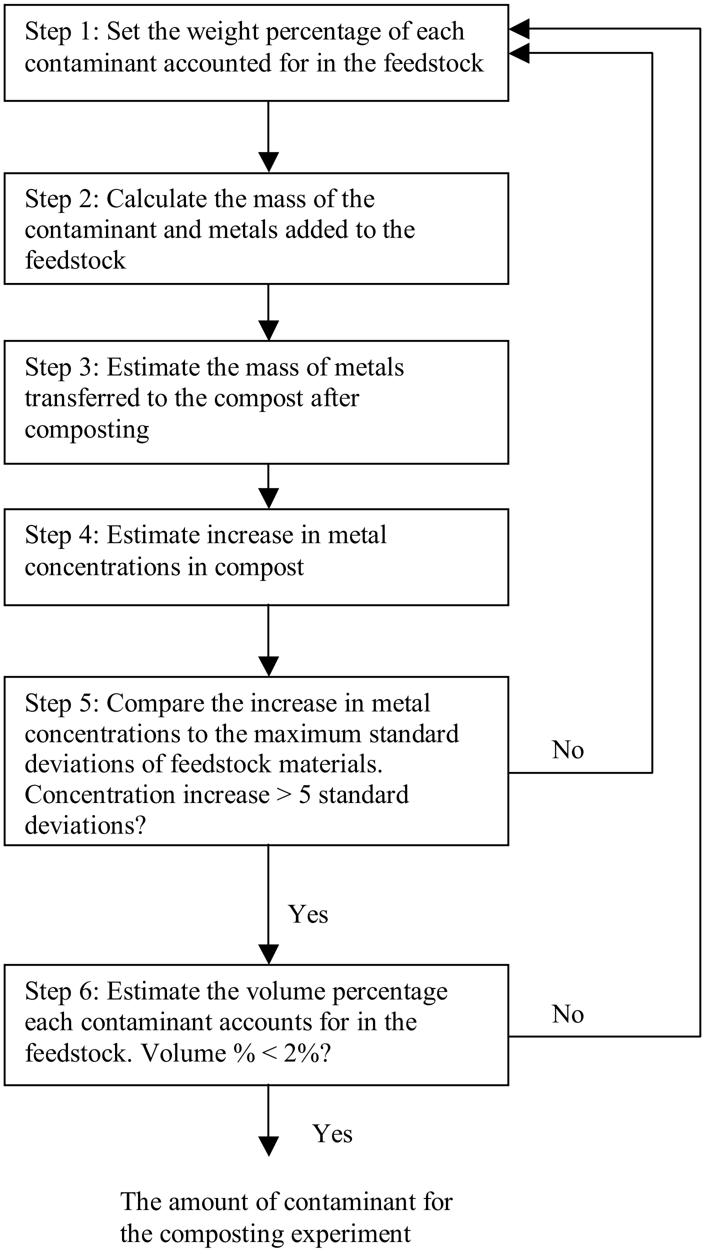

Figure 4-1 Procedures for determination of the amount of each type of contaminant (Adapted from Ge 2007).

Following the same procedures illustrated in Figure 4-1, the amount of each type of contaminant added was determined and summarized in Table 4-5. The weight ratio of zinc in each alkaline battery was set to 25% (Ge 2007). To simplify the calculations, the copper wires and electronic cables used in this experiment were cut to 40 cm in length.

Table 4-5 Summary of the contaminant addition in this experiment.

Contaminant	**Weight ratio of feedstock (ww)**	**Volume ratio of feedstock (ww)**	**Total amount, g (pieces)**	**Weight ratio of trace metal**	**Mass transfer g g^{-1}**	**Predicted metal increase, mg kg^{-1} dry compost**
High quality AA alkaline batteries	1.5%	0.05%	1500 (60)	Zn 25%	Zn 1%	Zn 75.00
Low quality AA alkaline batteries	1.5%	0.05%	1500 (60)	Zn 25%	Zn 1%	Zn 75.00
Galvanized nails	1.22%	0.012%	1220 (223)	Zn 99%	Zn 4.24%	Zn 1045.42
Zn-plated screws	1.22%	0.017%	1220 (308)	Zn 98%	Zn 5.52%	Zn 1342.03
Copper wire	1.22%	0.009%	1220 (97)	Cu 100%	Cu 1.59%	Cu 388.55
Electronic cable	1.22%	0.27%	9104 (97)	Cu 100%	Cu 1.59%	Cu 388.55

4.2.3.2 Experiment operation

Seven treatments of the composting experiment were carried out under the same experimental conditions (ambient temperature, aeration). One treatment was the control (without the addition of any contaminants), which was conducted to establish a background metal level. The other six treatments were carried out with the addition of each type of contaminant.

The experiment lasted for 21 days at the thermophilic composting stage. Feedstock materials together with the amendments were well mixed to achieve a good homogeneity. Water was added to reach 70% moisture content. Except for the control run, the calculated amount of each type of contaminant was scattered evenly through the feedstock mixtures before the whole was loaded into the bioreactor. Time = 0 was set as the feedstock preparation day.

As a routine operation, all of the seven bioreactors were turned at the same time at two or three day intervals to achieve substrate mixing. Each turning lasted for 10 minutes. Substrate bulk density, height and oxygen percent were measured in-situ before each turning. Sugar as the amendment was added while the reactor turned. To maintain the compost moisture content of 70%, water was added constantly throughout the process.

At the end of 21 days, all materials were removed from the bioreactor and all the contaminants were recovered. A metal detector was used to facilitate the collection of the metal contaminants such as nails, screws and copper wires.

4.2.3.3 Process monitoring

In order to monitor the composting condition, feedstock and compost samples were taken during the experiment for physical and chemical characterization including the compost's pH, electrical conductivity, and moisture content. Before the feedstock was loaded into the reactor, three samples (mass around 60g) were taken from different locations of the feedstock material randomly for feedstock characterization. During the 21 days of composting, the sampling was conducted at each turning event. With the reactor was turning, two samples (mass around 60g) were taken from different locations of the substrate material randomly. This random collection ensures that all substrate materials have equal opportunity to be tested.

At each turning, the pure space oxygen content was measured in-situ using an oxygen probe (OT-21, Demista Instruments). The bulk density of the feedstock and the compost product were measured in accordance with TMECC Section 03.01-C Field Density, Free Airspace and Water-holding Capacity (TMECC 2001). The height of the compost substrate was also recorded.

4.2.3.4 Metal analysis

In total, 22 elements including Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mo, Ni, P, Pb, S, Se, Si, Ti, V, and Zn were examined in the feedstock materials and compost products for each treatment. Three samples were taken at different locations of the compost feedstock randomly before composting. After the 21-day composting process, two samples (10-15 g) were taken from each treatment (including the control). To ensure that the collected samples are representative of the whole compost product, the grid method was used. All samples were dried at 70^{o}C for 48 hours and ground to 8 mm using a Wiley Mill (Laboratory Mill Model 4, Thomas Scientific, USA). To avoid cross-contamination, the grinder was vacuum cleaned between each sample. The eleven trace elements listed in the CCME guideline: Cd, Ni, Zn Cu Pb, Hg, Co, As, Mo, Se and Cr, were assessed as the concerning metals that would be released from the tested contaminants. All analyses were performed under the same conditions and in the same manner.

For the galvanized nails, Zn-plated screws and copper wires, the contaminant weight losses from the contaminants were also measured to validate the metal mass transfer proposed in Table 4-3. Twelve specimens of each contaminant were prepared followed the same method illustrated in Chapter 3, Section 3.2.2.2. Each specimen was weighed before and after the exposure to the composting environment using an analytical balance (AB204-S/FACT, Mettler Toledo, Switzerland) with an accuracy of 0.0001g.

4.2.3.5 Statistical analysis

Each selected contaminant is considered as an independent variable and is set as one treatment. A control (without contaminants added) was also carried out to detect any hidden variables and to establish a background metal level. Eleven dependent variables: As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn concentrations were measured to evaluate the response resulting from each treatment. The feedstock and composting conditions remained the same for all treatments and were considered as constants.

One-way variance analysis (ANOVA) was carried out using SigmaPlot 11.0 to compare the metal concentrations of different treatments. When significant p-values ($P<0.05$) were obtained, the Holm-Sidak test was carried out to compare the differences between each treatment and the control.

4.3 Results and Discussion

4.3.1 Composting Condition

4.3.1.1 Temperature

Temperatures at 60 cm and 20 cm from the bottom of the reactor were monitored throughout the 21 day composting process. The temperature profiles in each treatment are provided in Appendix B, Figure B-1 to Figure B-7. Due to the fact that the height of the compost kept reducing as the experiment proceeded, the top temperature probes were closer to the reactor headspace towards the end of the experiment. This may result in an underestimation of the real values. Therefore, only the temperatures monitored from the bottom probes are illustrated in Figure 4-2. Each value indicates the average temperature of every 24 hours.

The temperature profiles of all treatments showed similar trends. During the first three days, temperatures in all treatments increased rapidly from around 20°C to above 45°C, which suggests that a high rate of microbial degradation happened in all treatments. The thermophilic ($>55^0$C) composting stage was reached on day 3 in the treatment of copper wires and electronic cables. From day 6, the thermophilic composting stage was reached in all treatments and maintained until the end of the experiment. The variations among all treatments were high during the first week. This can be due to the fact that the composting substrate was heterogeneous during the early stage of composting. Since the turning of the substrate material was conducted constantly throughout the process, a better mixing of the substrate materials was achieved. The variations became smaller towards the end of the process. The temperature is considered as a constant in the statistical analysis of this study.

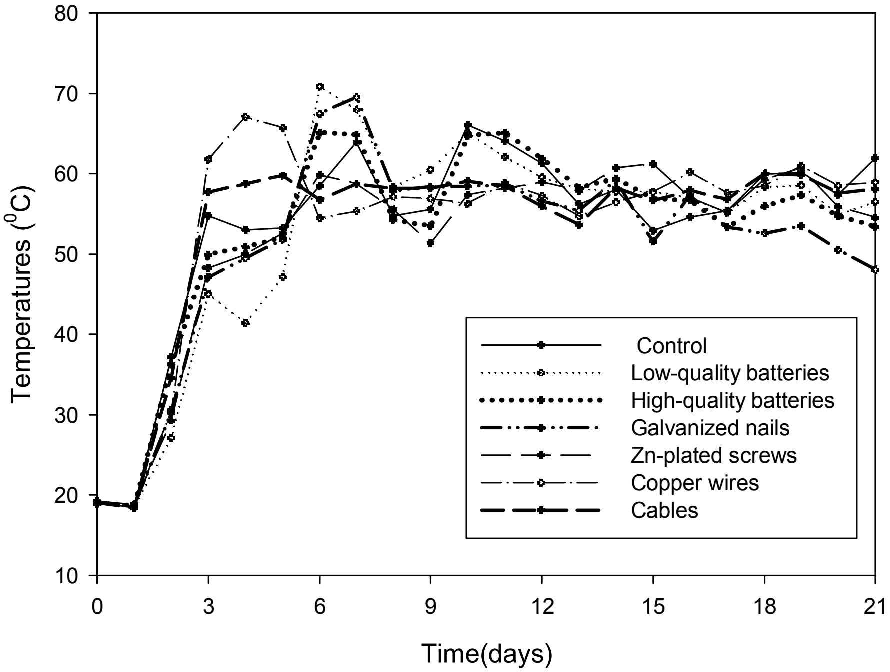

Figure 4-2 Temperature (^{0}C) profiles in all treatments during 21 days of composting process.

4.3.1.2 pH and EC

The changes in the pH values of the composting substrate show similar trends in each treatment (Figure 4-3). The composting feedstock combined with the peat moss had a pH value of 7.1. While the composting proceeded, an increase in pH was observed in all the treatments on day 4. Thereafter, as the pH control by adding sugar took effect, pH values declined to around 5.0 towards the end of the composting process. The pH differences among all the treatments were high in the first week, which may be due to the fact that the substrate materials were very bulky and heterogeneous. As turnings were conducted every two or three days, the variations in pH values between each treatment became smaller from the second week on. The pH control by adding amendment was shown to be effective in this experiment.

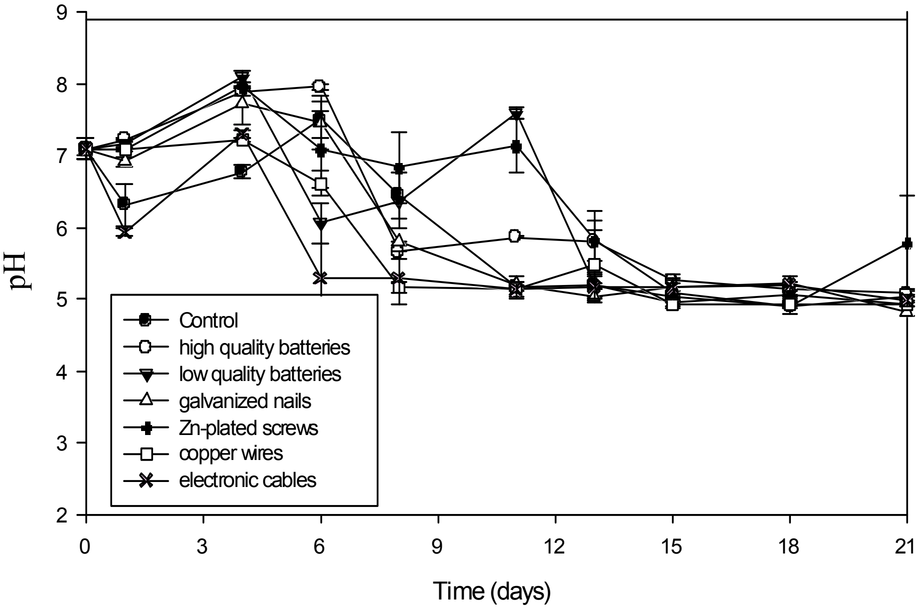

Figure 4-3 pH profile during 21 days composting. Each value is the mean of two replications ± 1 standard error of the mean.

Through the integration of pH values in each treatment to the exposure time (t = 21 days), the results show that the variations between each treatment is less than one pH unit. Therefore, the compost pH is considered as a constant in the following statistical analysis.

The electrical conductivity of the composting substrate was summarized in Table 4-6. The values in all treatments increased slightly during the process. The maximum variation among all treatments was observed on day 4, which was 0.574 ms cm^{-1}.

Table 4-6 Electrical conductivity (EC) (ms cm^{-1}) (mean ± 1 standard error) in all treatments during 21 days of composting.

Time (days)	Control	High quality batteries	Low quality batteries	Galvanized nails	Zn-plated screws	Copper wires	Electronic cables
1	3.016 ± 0.400	3.732 ± 0.160	3.116 ± 0.329	3.550 ± 0.039	3.358 ± 0.417	2.957 ± 0.162	2.542 ± 0.033
4	2.978 ± 0.400	3.896 ± 0.466	2.733 ± 0.007	3.161 ± 0.123	3.641 ± 0.028	2.245 ± 0.311	2.666 ± 0.173
6	3.689 ± 0.014	4.223 ± 0.085	3.751 ± 0.086	3.840 ± 0.040	3.141 ± 0.307	3.022 ± 0.149	3.553 ± 0.134
8	3.367 ± 0.039	3.558 ± 0.300	3.820 ± 0.041	3.705 ± 0.054	4.646 ± 0.148	3.695 ± 0.128	3.873 ± 0.063
11	3.296 ± 0.072	4.298 ± 0.424	4.496 ± 0.023	4.170 ± 0.153	4.269 ± 0.103	3.547 ± 0.043	4.312 ± 0.060
13	3.296 ± 0.072	3.951 ± 0.115	3.365 ± 0.093	4.077 ± 0.205	3.541 ± 0.062	3.658 ± 0.305	3.261 ± 0.103
15	3.849 ± 0.163	5.270 ± 0.090	3.807 ± 0.058	4.162 ± 0.138	4.121 ± 0.108	3.708 ± 0.298	3.697 ± 0.002
18	4.107 ± 0.043	4.196 ± 0.061	4.448 ± 0.232	4.033 ± 0.121	3.980 ± 0.091	3.334 ± 0.481	3.944 ± 0.072
21	3.478 ± 0.012	3.985 ± 0.034	3.763 ± 0.268	3.941 ± 0.074	3.955 ± 0.147	3.499 ± 0.141	3.368 ± 0.155

4.3.2 Metal Mass Transfer

For ferrous and non-ferrous contaminants (galvanized nails, Zn-plated screws and copper wires), the weight loss measurement was conducted to estimate the metal mass transfer in this experiment. The results are presented in Table 4-7. The raw data is given in Appendix B, Section B.4. After 21 days of exposure to the composting environment, the galvanized nails have the highest mass transfer of zinc, which is 4.61×10^{-2} g g^{-1}. For copper wires, the mass transfer of copper is 1.14×10^{-2} g g^{-1}.

Table 4-7 Contaminant weight loss (mean of twelve replications ± standard deviation) (g cm^{-2}) and metal mass transfer (g g^{-1}) after being exposed to 21 days in a composting environment.

Contaminant	Concerned Metal (weight ratio)	Weight Loss (g cm^{-2} contaminant)	Mass Transfer of Trace Metal (g g^{-1} contaminant)
Galvanized nail	Zn (99%)	$2.42\times10^{-2} \pm 1.03\times10^{-2}$	Zn: 4.61×10^{-2}
Zn-plated screw	Zn (98%)	$2.35\times10^{-2} \pm 1.08\times10^{-2}$	Zn: 3.42×10^{-2}
Copper wire	Cu (100%)	$6.00\times10^{-3} \pm 2.99\times10^{-3}$	Cu: 1.14×10^{-2}

4.3.3 Metal Analysis

4.3.3.1 Metal increase in composts

Table 4-8 shows the trace metal content of composts from all treatments. Each value is the mean of two replicates (the raw data is given in Appendix B, Section B.5). Among all values, 13% of them show a relative standard deviation that is higher than 50%. The variations could be reduced by increasing the number of samples collected from each reactor.

The one-way variance analysis (ANOVA) and the Holm-Sidak test were used to evaluate the response of the trace metal contents (dependent variables) resulting from each treatment. The result is given in Appendix D. The concentrations of the elements arsenic, copper and zinc are significantly different ($P<0.01$) among all the treatments at $\alpha = 0.05$. Concentrations of cobalt and lead also differ ($P<0.05$) between each treatment, while no statistically significant difference ($P>0.05$) was observed for the concentrations of cadmium, chromium, mercury, molybdenum, nickel and selenium.

Table 4-8 Compost trace metal content (mg kg^{-1} dry weight) after 21 days of composting. Mean of two replicates (standard deviation).

Element	Control	High quality battery	Low quality battery	Galvanized nail	Zn-plated screw	Copper wire	Electrical cable
As	0.58 (0.19)	0.44 (0.04)	1.57 (0.03)	0.46 (0.00)	0.39 (0.09)	0.63 (0.23)	0.59 (0.14)
Cd	0.14 (0.01)	0.11 (0.01)	0.15 (0.04)	0.09 (0.01)	0.09 (0.00)	0.11 (0.03)	0.09 (0.00)
Co	0.61 (0.09)	0.52 (0.06)	1.34 (0.34)	0.54 (0.03)	0.44 (0.09)	0.70 (0.21)	0.53 (0.07)
Cr	5.07 (0.46)	3.19 (0.41)	21.89 (17.71)	8.74 (6.91)	3.16 (0.68)	7.37 (4.79)	5.02 (1.60)
Cu	8.00 (0.38)	5.58 (0.67)	27.90 (7.82)	5.17 (0.68)	4.70 (0.73)	215.79 (15.61)	16.05 (1.17)
Hg	0.03 (0.00)	0.02 (0.00)	0.14 (0.12)	0.06 (0.06)	0.02 (0.00)	0.05 (0.04)	0.02 (0.01)
Mo	1.66 (0.05)	1.55 (0.02)	6.56 (4.04)	2.95 (2.25)	1.21 (0.12)	2.12 (1.40)	1.33 (0.22)
Ni	3.58 (0.36)	3.29 (0.39)	11.92 (5.34)	4.47 (2.25)	2.20 (0.40)	4.46 (1.99)	3.44 (0.14)
Pb	1.85 (0.28)	1.51 (0.23)	4.78 (1.83)	1.63 (0.51)	1.15 (0.14)	1.79 (0.54)	1.70 (0.09)
Se	<0.1	<0.1	0.26 (0.11)	0.16 (0.04)	<0.1	0.15 (0.05)	0.12 (0.03)
Zn	58.11 (1.02)	71.45 (6.48)	128.41 (15.99)	264.84 (64.08)	105.55 (13.37)	57.15 (3.79)	58.48 (3.50)

The comparison of the predicted and observed metal increases in the compost is presented in Table 4-9. The predicted metal increases are calculated based on the observed metal mass transfer from this study (Table 4-7). According to the monitoring of the compost heights, moisture content and bulk density at the end of the process, the compost mass reduction in each treatment was calculated and used in the determination of the compost dry weight. The observed metal increase is calculated based on the concentrations of the concerned metals from each treatment with the reduction of the values in the control. A sample calculation is provided in Appendix F.

Table 4-9 Comparison of the predicted and the observed metal increases in the compost from each treatment.

Contaminant	Mass transfer ($g\ g^{-1}$)	Predicted metal increase, (mg kg^{-1} dry compost)	Observed metal increase, (mg kg^{-1} dry compost)	Mass of metal released from contaminant (g)	Mass of metal detected in compost (g)
High quality AA alkaline batteries	Zn 1%	Zn 88.72	Zn 13.34	Zn 3.75	Zn 0.56
Low quality AA alkaline batteries	Zn 1%	Zn 79.00	Zn 70.30	Zn 3.75	Zn 3.34
Galvanized nails	Zn 4.61%	Zn 791.55	Zn 206.73	Zn 42.08	Zn 10.99
Zn-plated screws	Zn 3.42%	Zn 1419.69	Zn 47.43	Zn 56.04	Zn 1.87
Copper wire	Cu 1.14 %	Cu 322.38	Cu 207.79	Cu 13.91	Cu 8.96
Electronic cable	Cu 1.14 %	Cu 328.33	Cu 8.05	Cu 13.91	Cu 0.34

All observed metal increases were lower than the predicted values. The over estimation of the metal mass transfers is a possible reason for this. For example, for the high quality batteries, the mass transfer of zinc is much lower than the assumed 1%. For the electronic cables, the transfer of copper might be much lower than 1.59%, which is assumed to be the same as copper wires. Another reason could be the uneven distribution of the released trace metals in the composting substrates. Although the turning was carried out every two or three days, it is difficult to achieve a complete mixing of all materials in each reactor. The metal released from each contaminant is likely concentrated in the surrounded materials instead of distributed evenly in the whole substrate. This can lead to an underestimation of the actual metal increase from the contaminant. To achieve a higher recovery of the actual metal increase, two improvements are recommended in future studies: 1) extending the substrate mixing time; 2) increasing the number of samples collected from each reactor and ensuring that the samples were collected from various locations in the reactor.

4.3.3.2 Impact of contaminants on compost metal content

In order to investigate the impact of each individual contaminant on the metal contents (including elements arsenic, copper, zinc, cobalt and lead) of the composts, the Holm-Sidak test was carried out to compare the differences between each treatment and the control group.

The arsenic and cobalt content in the composts was observed to be significantly affected by the addition of low quality batteries (Figure 4-4, Figure 4-5). The concentrations of arsenic and cobalt were approximately three times and two times higher, respectively, than the values in the control. No significant difference was observed in the other treatments, which suggests that the low quality battery is the only contaminant that resulted in an increase of arsenic and cobalt content in the compost product. Compared with the CCME category A limit, which is 13 mg kg^{-1} dry weight for arsenic and 34 mg kg^{-1} dry weight for cobalt, the arsenic and cobalt released from the low quality batteries are 7.6% and 2.1% of the limit, respectively.

Contaminants of copper wires, low quality batteries and electronic cables were all observed to have an effect on the copper content in the composts (Figure 4-6). However, the statistical analysis revealed that only the treatment with the addition of copper wires shows a significant difference in the levels of copper, nearly 26 times higher than the concentration in the control. Compared with the CCME category A limit for copper (400 mg kg^{-1} dry weight), copper wires contributed to 51.9% of the limit concentration in the composts from this experiment.

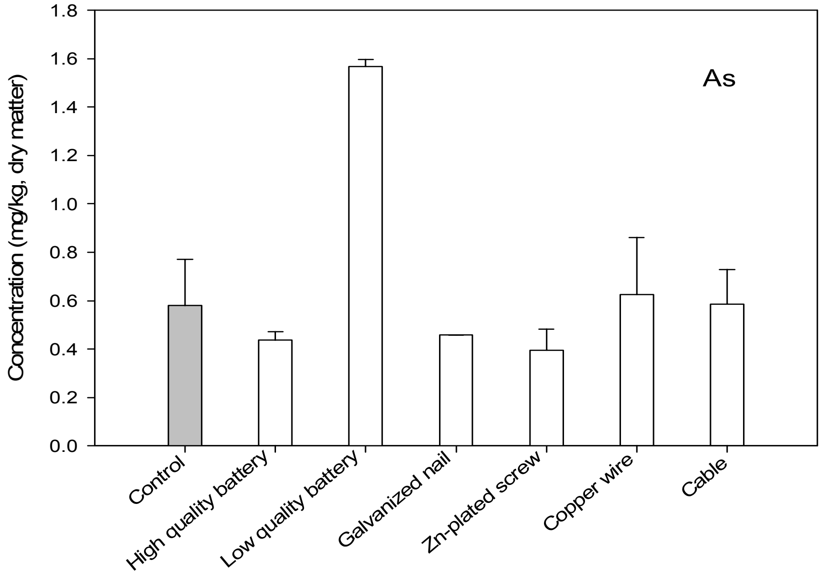

Figure 4-4 Concentrations of arsenic in composts after the 21 day composting process.

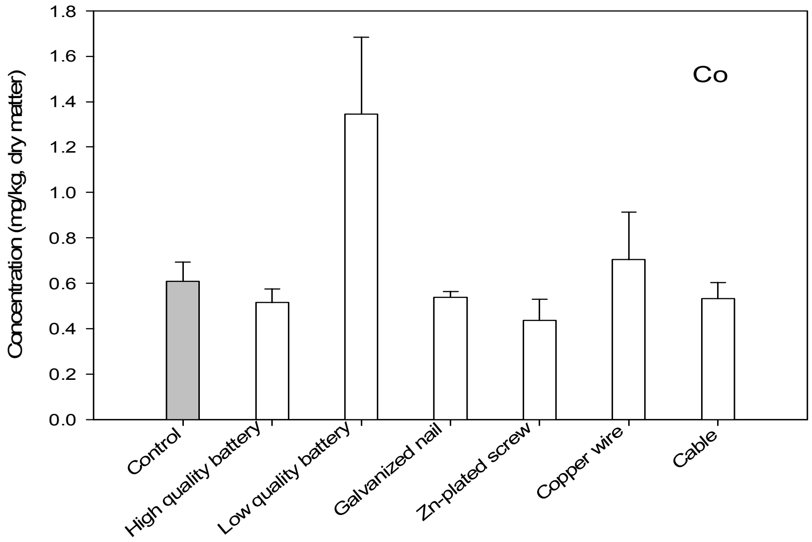

Figure 4-5 Concentrations of cobalt in composts after the 21 day composting process.

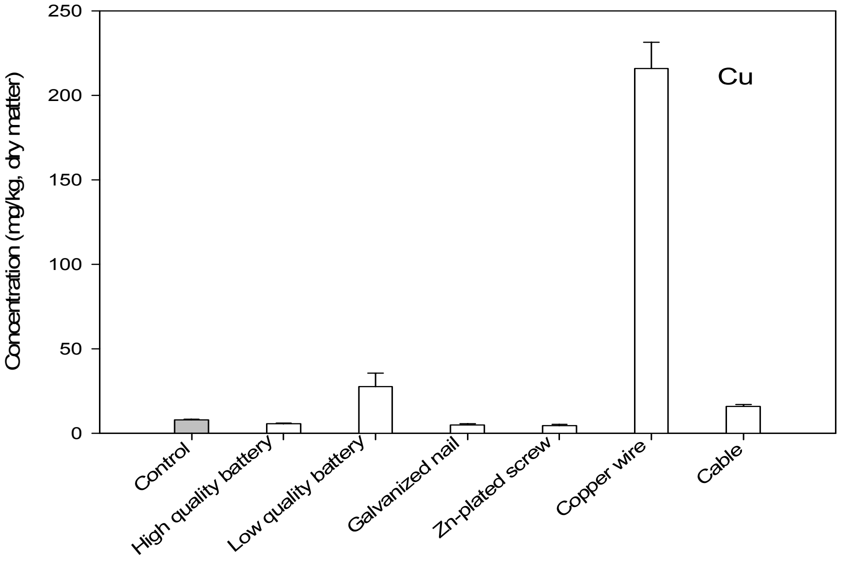

Figure 4-6 Concentrations of copper in composts after the 21 day composting process.

Composts from the treatments with the low quality batteries, galvanized nails and Zn-plated screws all showed an increase in the zinc content (Figure 4-7). The galvanized nails show a significant difference in the zinc level compared with the control. The concentrations in the treatments with the addition of low quality batteries and Zn-plated screws are also much higher than in the control. However, the differences are not high enough to exclude the possibility that they may be due to the sampling variability. Therefore, the galvanized nail is the only contaminant that raised concern on the zinc content of composts, which is 29.5% of the CCME category A limit, after the 21 day composting process.

The highest concentration of lead was observed in the composts associated with the addition of low quality batteries, which is 4.78 mg kg^{-1} (dry weight) in average. Composts from the other treatments were not shown to have a significant level of lead after the 21 day composting process (Figure 4-8). The CCME category A limit for lead is 150 mg kg^{-1} (dry weight). Thus, the lead released from the low quality batteries is 2.0% of the limit.

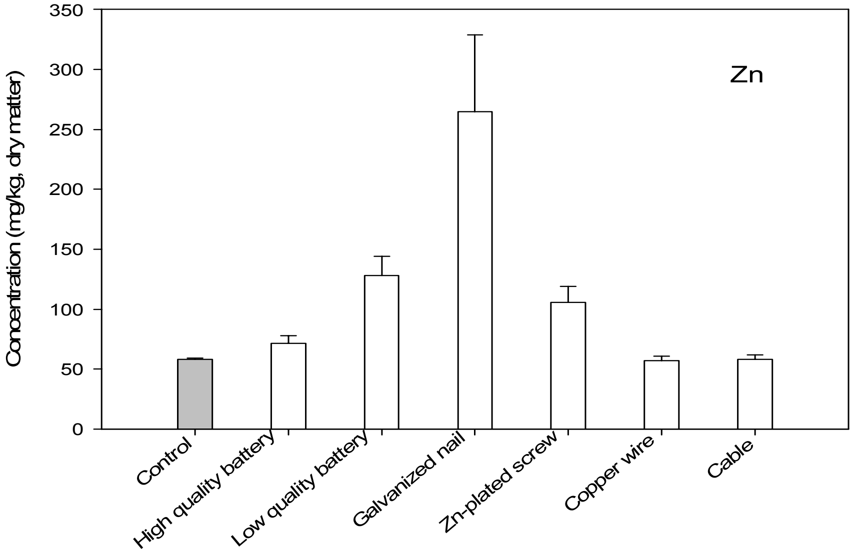

Figure 4-7 Concentrations of zinc in composts after the 21 day composting process.

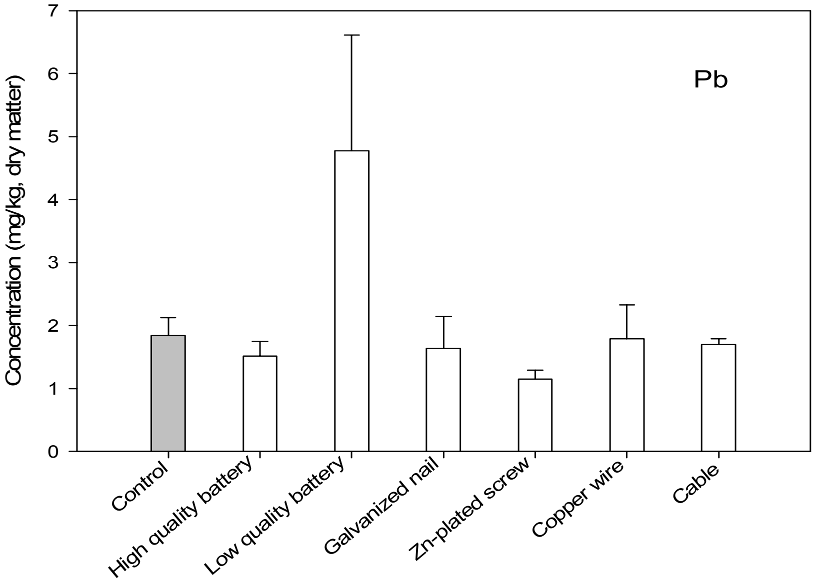

Figure 4-8 Concentrations of lead in composts after the 21 day composting process.

4.3.3.3 Effect of contaminant characteristics

The six types of contaminants were divided into three groups to investigate the influence of contaminant characteristics on the trace metal content of composts.

As is shown in Table 4-10, the characteristic of quality was assessed between the two treatments associated with alkaline batteries. Higher concentrations of all eleven elements were observed in the treatment of batteries with the lower quality. According to the statistical analysis, arsenic and zinc are the two metals that significantly differed ($P<0.05$) in their concentrations between the two treatments. This result is in agreement with the report by Jennings (2004), which suggested that the low quality alkaline battery had a higher leakage rate of pollutants when they were exposed to a hostile environment. Therefore, the quality of batteries (for example the construction) is shown to be a significant characteristic that can influence the metal release to the composts.

Table 4-10 Comparisons of the compost metal concentrations (mean of two replicates ± standard deviation) (mg kg^{-1} dry weight) between treatments with the addition of high quality batteries and low quality batteries[a].

Element	High Quality Battery	Low Quality Battery
As	0.44±0.04a	1.57±0.03b
Cd	0.11±0.01a	0.15±0.04a
Co	0.52±0.06a	1.34±0.34a
Cr	3.19±0.41a	21.89±17.71a
Cu	5.58±0.67a	27.90±7.82a
Hg	0.02±0.00a	0.14±0.12a
Mo	1.55±0.02a	6.56±4.04a
Ni	3.29±0.39a	11.92±5.34a
Pb	1.51±0.23a	4.78±1.83a
Se	<0.1a	0.26±0.11a
Zn	71.45±6.48a	128.41±15.99b

Notes: [a] for each type of element, data with the same letter does not differ significantly at the 5% level (t-test distribution).

The effect of contaminant surface area to mass ratio is evaluated by the treatments with the additions of galvanized nails and Zn-plated screws (Table 4-11). Higher concentrations of all 11 elements were associated with the galvanized nails. However, the statistical analysis revealed that the difference is not great enough to reject the possibility that it is due to random sampling variability ($P>0.05$). Therefore, based on the experimental results, the surface to mass ratio does not have a significant effect on the release of zinc.

Table 4-11 Comparisons of the compost metal concentrations (mean of two replicates ± standard deviation) (mg kg^{-1} dry weight) between treatments with the addition of galvanized nails and Zn-plated screws[a].

Element	Galvanized Nail	Zn-plated Screw
As	0.46±0.00a	0.39±0.09a
Cd	0.09±0.01a	0.09±0.00a
Co	0.54±0.03a	0.44±0.09a
Cr	8.74±6.91a	3.16±0.68a
Cu	5.17±0.68a	4.70±0.73a
Hg	0.06±0.06a	0.02±0.00a
Mo	2.95±2.25a	1.21±0.12a
Ni	4.47±2.25a	2.20±0.40a
Pb	1.63±0.51a	1.15±0.14a
Se	0.16±0.04a	<0.1a
Zn	264.84±64.08a	105.55±13.37a

Notes: [a] for each type of element, data with the same letter does not differ significantly at the 5% level (t-test distribution).

The effect of the protective covering was evaluated between the treatment with the addition of copper wires and electronic cables (Table 4-12).

Table 4-12 Comparisons of the compost metal concentrations (mean of two replicates ± standard deviation) (mg kg^{-1} dry weight) between treatments with the addition of copper wires and electronic cables[a].

Element	Copper wire	Electronic Cable
As	0.63±0.23a	0.59±0.14a
Cd	0.11±0.03a	0.09±0.00a
Co	0.70±0.21a	0.53±0.07a
Cr	7.37±4.79a	5.02±1.60a
Cu	215.79±15.61a	16.05±1.17b
Hg	0.05±0.04a	0.02±0.01a
Mo	2.12±1.40a	1.33±0.22a
Ni	4.46±1.99a	3.44±0.14a
Pb	1.79±0.54a	1.70±0.09a
Se	0.15±0.05a	0.12±0.03a
Zn	57.15±3.79a	58.48±3.50a

Notes: [a] for each type of element, data with the same letter does not differ significantly at the 5% level (t-test distribution).

The concentrations of copper are significantly different between the two treatments, which suggested that the plastic sheath of the cable is an important factor in reducing the copper released into the composts.

4.4 Summary and Conclusions

Six types of MSW contaminants including high quality alkaline batteries, low quality alkaline batteries, galvanized nails, Zn-plated screws, copper wires and electronic cables were exposed to a composting environment for 21 days. To investigate the impact of each contaminant on the trace metal content in compost product, statistical analysis was carried out based on the assumption that the composting conditions (feedstock, temperature, aeration) were remained the same in all treatments. Variations were observed in the temperatures and substrate pH values during the early stage of the composting process. This may be due to the substrate heterogeneity. A more homogeneous substrate can be achieved by extending the material mixing time.

Concentrations of 11 trace metals in compost product were determined after the composting process. The metal increases of composts due to the addition of contaminants were lower the predicted values. A higher recovery of the actual metal increase can be achieved by: 1) extending the substrate mixing time; 2) increasing the number of samples collected from each reactor and ensuring that the samples were collected from various locations in the reactor. According to the results of the statistical analysis, significant increase in the concentrations of arsenic, cobalt, copper, lead and zinc was observed in the composts. The low quality batteries were found to have a significant effect on the increase of arsenic, cobalt and lead content. Galvanized nails and copper wires were found to have a significant effect on the increase of zinc and copper, respectively.

Comparing the increased metal content in composts with the CCME Category A limit, copper wires contributed 51.9% of the maximum concentration for copper. Galvanized nails contribute 29.5% for zinc. The low quality batteries contribute 7.6% arsenic, 2.1% cobalt and 2.0% lead. Therefore, in order to ensure that the compost quality reaches the

CCME category A criteria, the copper wires presented in the composting feedstock raises most concern.

A possible source for the cobalt released from low quality batteries may be the pigment painted on the battery surface (Ge 2005). The arsenic and lead may come from the zinc powder, which is an important component of alkaline batteries (Ge 2005). For galvanized nails, the high level of zinc may come from the zinc layer coated on the base steel. The high level of copper released from the copper wires suggests that the contaminant made from bare copper is a main contributor of the copper content in composts.

In the interest of exploring the effect of contaminant characteristics on the compost metal content, comparisons of metal concentrations between treatments of two types of batteries, treatments of galvanized nails and Zn-plated screws, and treatments of coppers and cables were carried out. The results revealed that the quality of the batteries and the protective covering of the cable are important factors in influencing the metal transfer. Whereas no significant difference was observed in the concentration of zinc between the treatments of galvanized nails and Zn-plated screws, which suggests that the surface area to mass ratio is less likely to influence the metal release during the composting process. Therefore, the batteries that are poorly constructed and contaminants without any protective covering outside the bare metal are more likely to become contributors of trace metals in the compost product.

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CHAPTER 5 GENERAL DISCUSSION AND CONCLUSIONS

5.1 Research Overview

The centralized separation of non-compostable materials from the compostable organics is an approach applied by many composting facilities that use mixed municipal solid waste (MSW) as their composting feedstock. One drawback of this approach is the high trace metal content present in the finished compost products (Richard and Woodbury 1992). The study on the characterization of the composition of Edmonton's residential waste stream indicated that 61.2% of the wastes were compostable, which included food waste, yard waste and other organics. The other 38.8% was non-compostable, such as metals, plastics, glass and textiles (Ge 2007). During the process of waste storage and collection, the presence of the non-compostable materials can, potentially, release heavy metals into the compostable organics and result in the high levels of trace metals in the composts.

According to the literature review, batteries, ferrous, non-ferrous materials and electronic products were reported as the main contributors of trace metals in MSW. In order to improve the compost quality by reducing the levels of trace metals, it is important to know how much metal would be released from these contaminants during the composting process and how much would end up in the finished composts. Therefore, the impact of different contaminants on the trace metal content of compost was evaluated. This information could help the designers of the composting facilities to have a better knowledge of what type of contaminant is the main contributor of heavy metals to the compost and find the potential benefits of pre-treatment and feedstock manipulation in improving the compost quality.

5.2 General Discussion

5.2.1 Literature Review on the Main Contributors of Trace Metals

To investigate the main contributors of the high trace metal content in compost, a literature review on the metal content of different contaminants was carried out. Batteries were shown to have a contribution of 89%-98% mercury and 40%-55% zinc to the waste stream (Rosseaux et al. 1989; Maystre and Viret 1993; Rugg and Hanna 1992). The ferrous and non-ferrous materials such as metal alloys were shown to be the important contributors of cadmium, zinc, chromium, arsenic and nickel (Rugg and Hanna 1992). The electronic products contain trace metals such as lead, mercury, cadmium and arsenic (Ge 2005). According to Maystre and Viret (1993), electronic products contributed 32% copper, 12% zinc, 22% cadmium and 16% lead to the MSW.

Based on the literature review on the pathways of metal release from contaminants during the composting process, the method of corrosion weight loss measurement was proposed to quantify the mass of metal transfer.

5.2.2 Metal Mass Transfer during Composting

The first experimental trial was carried out to quantify the metal mass transfer during the composting process. With the hypothesis that the relative degree of acidity and the temperature are the two main factors that can influence the corrosion rate in a composting environment, the experiment was carried out in the thermophilic ($>55^{o}C$) composting stage using a low pH (pH from 4.6 to 7.4) and a high pH (pH from 7.8 to 8.9) feedstock. The low pH was maintained through the addition of sugar and peat moss. The higher levels of organic acids detected in the low pH compost substrate suggest that the pH control is effective.

The surface characterization of the tested contaminants after the exposure of a 21-day thermophilic composting process revealed that species such as chloride, sulphate and hydroxyl existing in the composting substrate formed corresponding corrosion products on the contaminant's surface. For example, Cu_2O and $CuCl_2$ were detected on the surface of the copper wire and the brass screw, which suggested copper ions were released to the environment through corrosion reactions. Iron was detected on the surface of galvanized nails and Zn-plated screws, which indicated that part of the zinc coating had come off the base steel and had been transferred to the composting environment.

The comparison of the weight loss between contaminants exposed to the low pH and high pH composting substrate indicated that the values were 1.5 to 7.5 times higher in the low pH environment. This suggests that the corrosion rate is accelerated by the acidic environment. Considering the worst-case scenario of corrosion during the composting process, only the result from the low pH treatment is discussed in this research. The highest mass transfer of trace metals were made by galvanized nails and Zn-plated screws, which released 0.0424 g g^{-1} and 0.0525 g g^{-1} zinc, respectively. The brass screws released 0.0191 g g^{-1} copper and 0.0107 g g^{-1} zinc. The copper wires released 0.0159 g g^{-1} copper. Based on these mass transfer values, to reach the quality criteria of the CCME category A compost, maximally 12.69 g Zn-plated screws, 25.12 g copper wires and 16.50 g galvanized nails could be disposed to every 1 kg compost (dry basis). The mass transfer of lead from the light bulb tails and chromium from the stainless steel flat washers was two orders of magnitude lower than the values from other contaminants. Thus they are not considered as the main contributors of trace metals.

5.2.3 Impact of Contaminants on Compost Trace Metal Content

The second experimental trial aimed to evaluate the impact of different contaminants on the trace metal content in the organic fraction of composts. Based on the literature review and the tested metal mass transfer from the first trial experiment, six types of MSW contaminants, which included high quality alkaline batteries, low quality alkaline batteries, galvanized nails, Zn-plated screws, copper wires and electronic cables, were added to the composting feedstock. The amount of contaminant added was based on Edmonton's waste sort result (Ge 2007). Significant increases in the concentrations of arsenic, cobalt, copper, lead and zinc were observed in the composts after the composting process.

In order to be in accordance with the CCME Category A limit for trace metal content (CCME 2005), the addition of copper wires raised the most concern since they contributed the greatest amount of trace metal in the composts (copper released from copper wires accounted for 51.9% of the CCME A maximum concentration). Galvanized nails ranked as the second most concerning contaminant since they contributed 29.5% of the CCME A limit for zinc. The low quality batteries contributed the most types of trace metal among all contaminants, which were arsenic, cobalt and lead. However, the increased levels of these metals were fairly low compared with the CCME A limit (7.6% for arsenic, 2.1% for cobalt and 2.0% for lead).

The increased copper content that resulted from the addition of copper wires was 13 times higher than that from electronic cables. This suggests that contaminants made from bare metal are more likely to be the contributors of trace metals than the ones with protective coverings. The zinc coating on the surface of galvanized nails was shown to be a major source of the high zinc content in the compost. The low quality alkaline batteries (not well constructed) were more likely to release the enclosed zinc powder, which could result in the increase of arsenic and lead in the compost. The increased cobalt could be resulted from the pigment painted on the battery surface. The high quality batteries were not shown to be a concern in the increase of compost trace metal content.

5.2 Conclusions

According to the literature review, the non-compostable contaminants which are mixed with the composting feedstock could result in the high trace metal content in the compost products. Contaminants such as batteries, ferrous, non-ferrous materials and electronic products are reported as the main contributors of trace metals in MSW. During the composting process, metal ions could be released from the contaminants to the composts through corrosion reactions.

The method of corrosion weight loss measurement was shown to be effective in quantifying the metal mass transfer during the composting process. The results indicated that copper wires, Zn-plated screws and galvanized nails were the most likely to release trace metals into compost products.

The metal increase in the compost that came from the addition of contaminants (batteries, ferrous, non-ferrous materials and electronic products) revealed that copper wires, galvanized nails and low quality alkaline batteries released significant levels of copper, zinc, arsenic, lead and cobalt to the compost products. The copper wires contributed 51.9% of the CCME A maximum concentration for copper. The galvanized nails contributed 29.5% of the CCME A maximum concentration for zinc. Thus they are the main contributors to the high trace metal content in the compost. In order to ensure that the compost quality reaches the CCME category A criteria, contaminants made from bare copper and contaminants with a zinc coating should be removed from the composting feedstock as much as possible. Batteries which are not well constructed could release arsenic, lead and cobalt to the compost product. Comparing with the CCME category A limit, the concentrations of these metals were relatively low (7.6% for arsenic, 2.1% for cobalt and 2.0% for lead). Thus batteries are not main contributors of the high trace metal content in the compost.

5.3 Recommendations for Future Research

This research only focused on investigating the metal mass transfer during a three-week active (thermophilic) composting process by assuming that the corrosion rate was accelerated under high temperatures. However, the corrosion could also occur during the feedstock mixing and the compost curing stages. Therefore, further studies on the metal transfer before and after the thermophilic composting process are recommended.

The statistical analysis of the impact of each contaminant on the compost trace metal content was carried out by assuming that the feedstock and composting conditions remained the same for all treatments. However, small variations were observed in the temperatures and substrate pH values among all treatments. This may be due to the fact that the substrate materials were bulky during the early stage of the composting process and the substrate heterogeneity was inevitable. Smaller variations could be achieved by extending the material mixing time.

All observed metal increases in compost were lower than the predicted values. This can be due to the uneven distribution of the released metals in the composting substrates. In order to achieve a higher recovery of the actual metal increase, two improvements are recommended: 1) extending the substrate mixing time; 2) increasing the number of samples collected from each reactor and ensuring that the samples were collected from various locations in the reactor.

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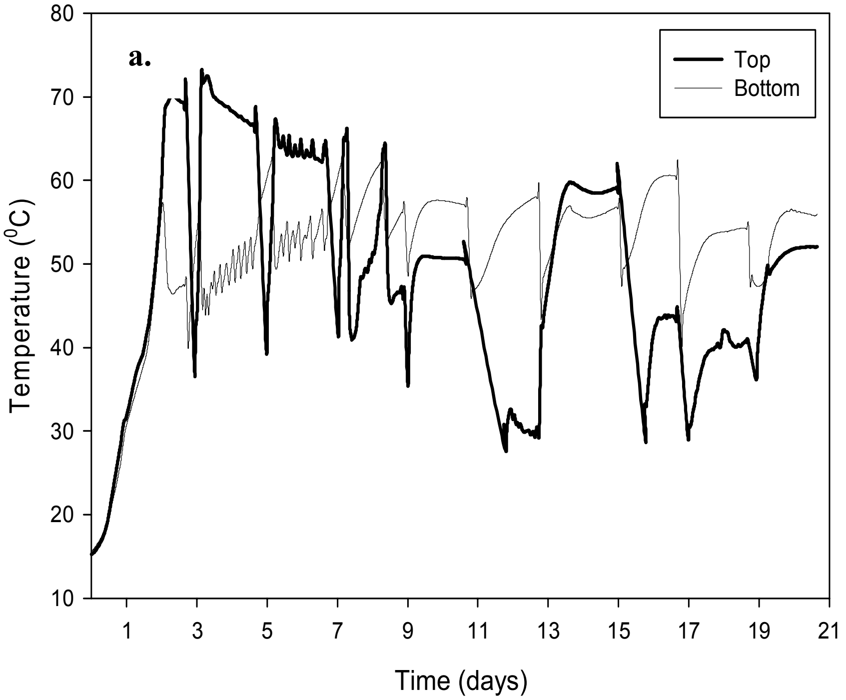
APPENDIX A RAW DATA FOR EXPERIMENTAL RESULTS (TRIAL 1)

A.1 Raw Data for Monitored Temperatures

Temperatures at 60 cm and 20 cm from the bottom of the reactor are indicated as top and bottom respectively in Figure A-1. The temperatures were monitored every hour during the three-week composting process. The oscillation of the temperature can be due to the turning of the compost material, which was conducted at two day intervals.



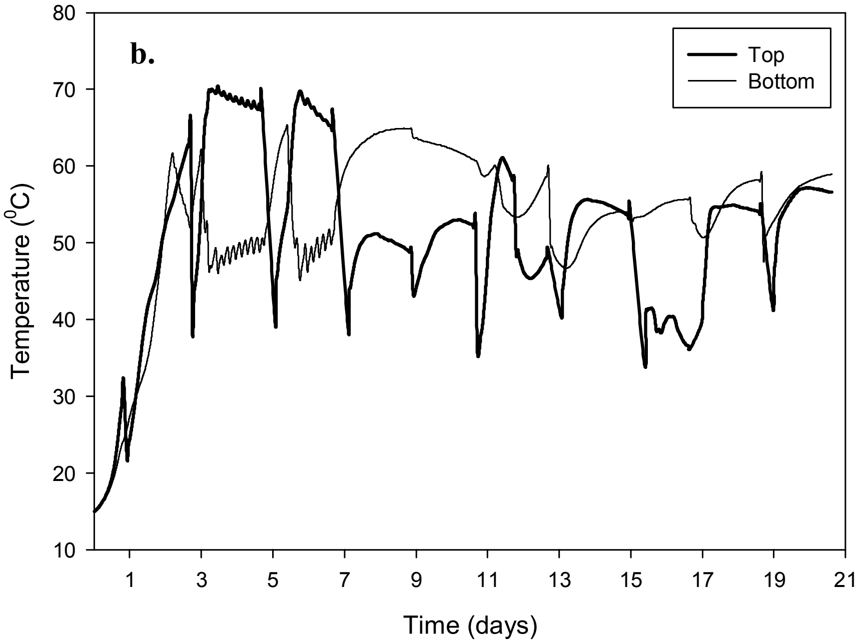


Figure A-1 Temperature (^{0}C) profiles during 21 days of composting process: (a) Hp-treatment (b) Lp-treatment.

A.2 Raw Data for pH and EC Values

The substrate pH and EC were measured at two days intervals (Table A-1). Each measurement was performed in triplicate.

Table A-1 Raw data for substrate pH and EC values in both treatments.

Time	Lp		Hp	
	pH	EC (ms/cm)	pH	EC (ms/cm)
April 3 2009	7.37	3.148	7.92	3.487
	7.66	2.170	7.75	3.229
	7.31	3.066	7.78	3.360
April 4 2009	7.39	2.836	7.92	3.405
	7.06	3.009	8.07	3.467
	7.09	3.077	7.96	3.495
April 6 2009	4.95	3.264	8.16	3.086
	6.86	3.127	8.49	2.772
	4.97	3.302	8.36	3.182
April 8 2009	5.51	3.634	8.44	2.905
	5.30	3.433	8.48	2.975
	6.47	3.605	8.44	3.272
April 10 2009	5.44	3.226	8.41	3.277
	4.79	3.343	8.44	3.496
	4.66	3.459	8.71	3.511
April 12 2009	5.03	3.243	8.62	3.533
	4.56	3.212	8.68	3.499
	4.21	3.178	8.67	3.474
April 14 2009	6.00	3.497	8.62	3.968
	4.54	3.378	8.63	3.732
	4.57	3.326	8.83	3.788
April 16 2009	5.91	3.466	8.82	3.677
	5.56	3.583	8.66	3.794
	4.70	3.518	8.91	3.845
April 18 2009	5.44	3.265	8.87	3.743
	5.12	3.447	8.79	3.823
	4.41	3.638	8.70	3.920
April 20 2009	4.69	3.720	9.24	4.226
	5.37	3.765	8.91	4.115
	4.36	3.771	8.97	3.946

Table A-1 (Continued) Raw data for substrate pH and EC values in both treatments.

Time	Lp		Hp	
	pH	EC (ms/cm)	pH	EC (ms/cm)
April 22 2009	4.75	3.572	8.83	3.935
	5.22	3.511	8.85	4.152
	4.54	3.458	8.75	4.037
April 24 2009	5.46	3.358	8.95	4.414
	5.02	3.756	8.87	4.315
	5.34	3.468	8.90	5.015

A.3 Raw Data for Acid Concentrations

The concentrations for all tested organic acids in the composting substrate are presented in Table A-2.

Table A-1 Raw data for acid concentrations in the composting substrate in both treatments during the composting process.

Time	ID	Acetic	Propionic	Isobutyric	Butyric	Isovaleric	Valeric
April 04	HP-1	4.859	0.044	0.027	0.022	0.012	0.010
	HP-2	9.313	0.085	0.008	0.006	0.014	0.017
April 08	HP-1	1.554	0.021	0.000	0.000	0.000	0.000
	HP-2	1.419	0.014	0.020	0.005	0.005	0.001
April 12	HP-1	1.292	0.033	0.014	0.006	0.005	0.004
	HP-2	1.405	0.905	0.414	1.937	0.307	0.019
April 16	HP-1	1.953	0.063	0.035	0.032	0.009	0.003
	HP-2	1.082	0.037	0.017	0.005	0.006	0.004
April 20	HP	1.456	0.059	0.010	0.014	0.008	0.005
April 04	LP-1	3.979	0.349	0.011	0.418	0.009	0.007
	LP-2	5.442	0.007	0.007	0.009	0.009	0.011
April 08	LP-1	34.212	0.527	0.340	1.045	0.267	0.042
	LP-2	7.059	0.075	0.040	0.192	0.045	0.024
April 12	LP	73.292	0.655	0.234	1.170	0.299	0.016
April 16	LP-1	42.302	0.127	0.014	0.081	0.030	0.022
	LP-2	47.324	0.395	0.126	0.661	0.195	0.010
April 20	LP-1	58.961	1.075	0.093	1.955	0.130	0.012
	LP-2	88.293	0.298	0.158	0.934	0.230	0.041

A.4 Raw Data for Ion Concentrations

The concentrations for chloride, sulphate, magnesium, calcium and ammonium in the composting substrate are presented in Table A-3.

Table A-2 Ion concentrations in the composting substrate in both treatments during the composting process.

Sample ID	Amount mg/l Chloride	Amount mg/l Sulphate	Amount mg/l Magnesium	Amount mg/l Calcium	Amount mg/l Ammonium
Apr 4 lp- 1	58.6353	38.4435	9.9022	24.2694	1.0259
Apr 4 lp-2	49.9885	38.7709	9.2824	22.0236	0.9930
Apr 4 hp-1	51.1686	39.7963	10.0237	21.3211	3.0981
Apr 4 hp-2	53.4260	40.1017	10.6427	22.0762	3.6262
Apr 8 lp-1	31.0699	25.2690	12.7662	35.3949	2.5858
Apr 8 lp -2	56.1619	43.3626	7.4177	17.9487	3.3871
Apr 8 hp -1	63.5276	51.2239	6.3573	15.9754	2.3829
Apr 8 hp- 2	67.6107	52.9674	6.2480	15.4546	6.4306
Apr 12 lp-1	40.9844	32.4970	14.7896	29.4231	0.1793
Apr 12 lp-2	43.4855	34.0836	17.7207	38.5966	0.0663
Apr 12 hp-1	69.3052	51.7154	6.0514	17.3888	3.4711
Apr 12 hp-2	71.2371	54.2940	6.1764	17.5888	2.7408
Apr 20 lp-1	49.3525	38.1361	23.8551	63.5229	1.1923
Apr 20 lp-2	49.1161	37.6307	19.2020	37.1694	0.0434
Apr 20 hp-1	83.7838	60.3301	6.1626	17.4310	4.4523
Apr 20 hp-2	86.1786	63.6334	5.6183	16.7449	5.1822

A.5 Raw Data for Other Monitored Composting Parameters

The substrate moisture content, oxygen content and the height of the composting pile were measured at each turning event. The raw data is presented in Table A-4 to Table A-6.

Table A-3 The moisture content (%) in the composting substrate in both treatments.

Time	Lp			Hp		
	Replicate 1	Replicate 2	Replicate 3	Replicate 1	Replicate 2	Replicate 3
April 3	73.1	75.2	69.7	70.9	74.8	76.0
April 4	72.4	71.9	72.2	75.6	73.7	72.7
April 6	76.7	77.8	78.1	77.0	77.1	76.5
April 8	76.2	73.4	74.9	82.3	69.1	78.5
April 10	75.5	71.8	77.1	76.9	75.0	75.7
April 12	73.3	69.7	72.9	75.5	75.8	75.3
April 14	69.6	70.5	74.0	69.6	75.3	75.1
April 16	71.4	70.6	72.5	75.6	75.4	74.6
April 18	71.0	75.9	72.7	76.6	75.8	77.5
April 20	66.3	77.4	72.9	75.5	75.5	76.4
April 22	76.6	74.3	73.7	76.6	74.7	73.2
April 24	70.1	72.4	71.5	76.1	75.9	73.5

Table A-4 The oxygen content in the composting substrate in both treatments.

Time	Lp		Hp	
April 4 2009	3%	6%	7%	7%
April 6 2009	13%	14%	15%	17%
April 8 2009	13%	14%	13%	14%
April 10 2009	15%	11%	10%	13%
April 12 2009	12%	13%	7%	7%
April 14 2009	9%	8%	13%	12%
April 16 2009	11%	14%	14%	14%
April 18 2009	12%	12%	15%	16%
April 20 2009	8%	7%	12%	12%
April 22 2009	11%	12%	10%	10%
April 24 2009	15%	14%	14%	14%

Table A-5 The height (m) of the compost pile in both treatments before each turning event.

Time	Lp	Hp
April 3 2009	0.93	0.85
April 4 2009	0.91	0.86
April 6 2009	0.88	0.72
April 8 2009	0.79	0.68
April 10 2009	0.77	0.68
April 12 2009	0.69	0.62
April 14 2009	0.69	0.71
April 16 2009	0.72	0.56
April 18 2009	0.65	0.64
April 20 2009	0.60	0.51
April 22 2009	0.67	0.60
April 24 2009	0.59	0.45

A.6 Raw Data for Specimen Weight Losses

The specimen weight loss indicated the difference between the initial weight and the weight after being exposed to a three weeks composting environment at 55-70°C. The values for all replicates of each type of specimen were shown in Figure A-2 to Figure A-5. The minimum weight loss refers to the weight change before chemical cleaning, while maximum weight loss refers to the value after chemical cleaning. The average value ± 1 standard deviation is tabulated in Table A-8.

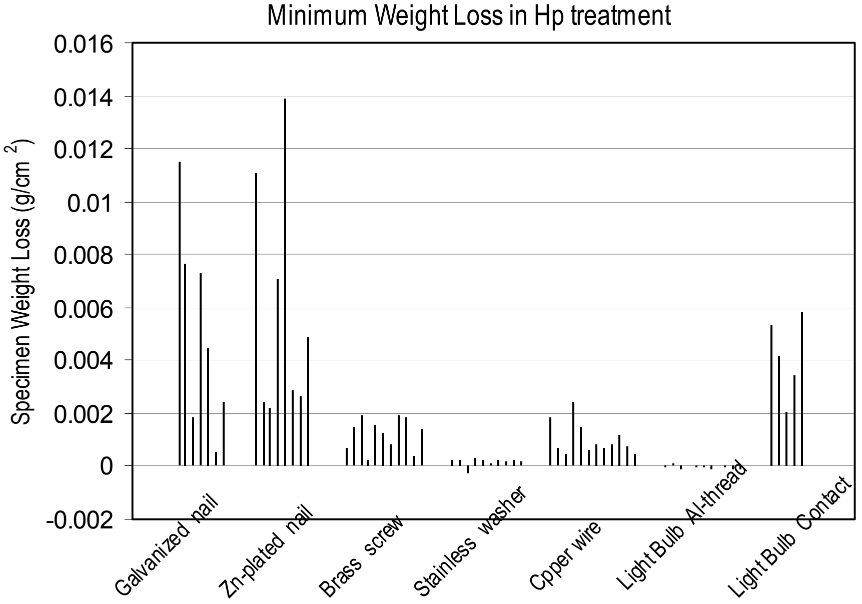


Figure A-2 Specimen weight losses (g cm^{-2}) before chemical cleaning in the Hp treatment.

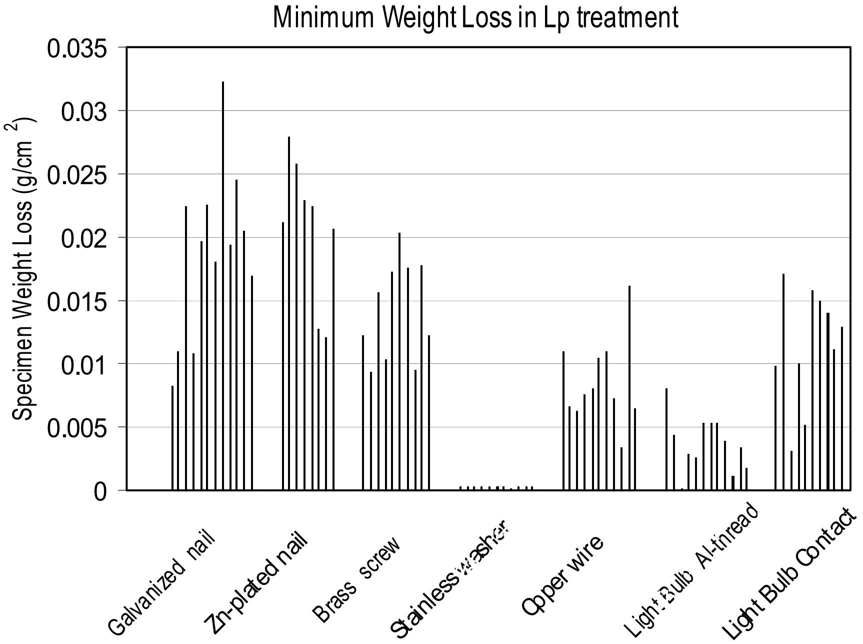


Figure A-3 Specimen weight losses (g cm^{-2}) before chemical cleaning in the Lp treatment.

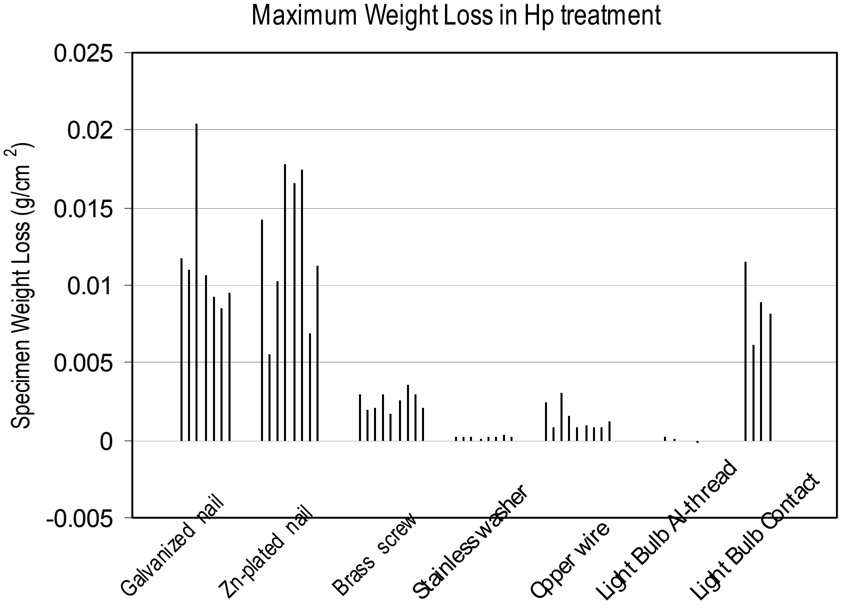


Figure A-4 Specimen weight losses (g cm^{-2}) after chemical cleaning in the Hp treatment.

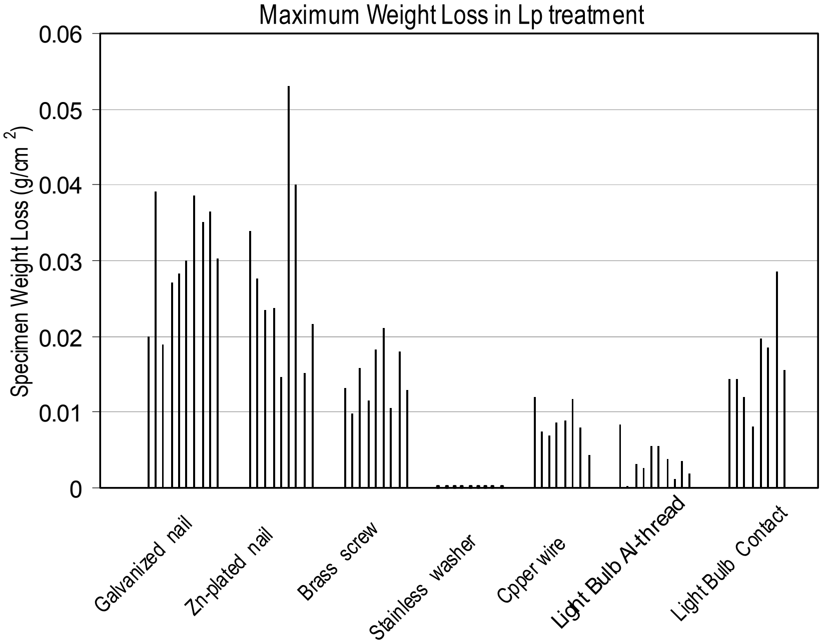


Figure A-5 Specimen weight losses (g cm^{-2}) after chemical cleaning in the Lp treatment.

Table A-7 Specimen weight loss (mean±standard deviation) (g cm^{-2}) after exposed to 21 days composting environment at 55-70^{o}C.

	Hp treatment		**Lp treatment**	
Contaminant	**Before chemical cleaning**	**After chemical cleaning**	**Before chemical cleaning**	**After chemical cleaning**
Galvanized nail	5.11×10^{-3} ± 3.90×10^{-3}	1.12×10^{-2} ± 0.41×10^{-2}	1.89×10^{-2} ± 0.66×10^{-2}	3.00×10^{-2} ± 0.71×10^{-2}
Zn-plated screw	5.89×10^{-3} ± 4.44×10^{-3}	1.25×10^{-2} ± 0.48×10^{-2}	2.07×10^{-2} ± 0.57×10^{-2}	2.81×10^{-2} ± 1.24×10^{-2}
Brass screw	1.24×10^{-3} ± 0.61×10^{-3}	2.52×10^{-3} ± 0.62×10^{-3}	1.42×10^{-2} ± 0.40×10^{-2}	1.46×10^{-2} ± 0.39×10^{-2}
Copper wire	1.11×10^{-3} ± 0.63×10^{-3}	1.14×10^{-3} ± 0.82×10^{-3}	7.44×10^{-3} ± 2.26×10^{-3}	8.50×10^{-3} ± 2.52×10^{-3}
Stainless steel flat washer	1.68×10^{-4} ± 1.58×10^{-4}	2.28×10^{-4} ± 0.47×10^{-4}	2.93×10^{-4} ± 0.30×10^{-4}	2.95×10^{-4} ± 0.30×10^{-4}
Light bulb tail Al-thread	$- 4.56\times10^{-5}$ ± 6.86×10^{-5}	$- 1.39\times10^{-5}$ ± 9.58×10^{-5}	3.43×10^{-3} ± 2.33×10^{-3}	3.55×10^{-3} ± 2.39×10^{-3}
Light bulb tail contact	4.18×10^{-3} ± 1.53×10^{-3}	8.66×10^{-3} ± 2.21×10^{-3}	1.14×10^{-2} ± 0.46×10^{-2}	1.64×10^{-2} ± 0.61×10^{-2}

APPENDIX B RAW DATA FOR EXPERIMENTAL RESULTS (TRIAL 2)

B.1 Raw Data for Monitored Temperatures

In the second experimental trial, temperatures in all treatments were monitored at one hour intervals throughout the 21 days composting process. Temperatures at 60 cm and 20 cm from the bottom of the reactor are illustrated as top and bottom in Figure B-1 to Figure B-7. The oscillations of the temperatures can be due to the turning of the compost material, which was conducted at two or three-day intervals.

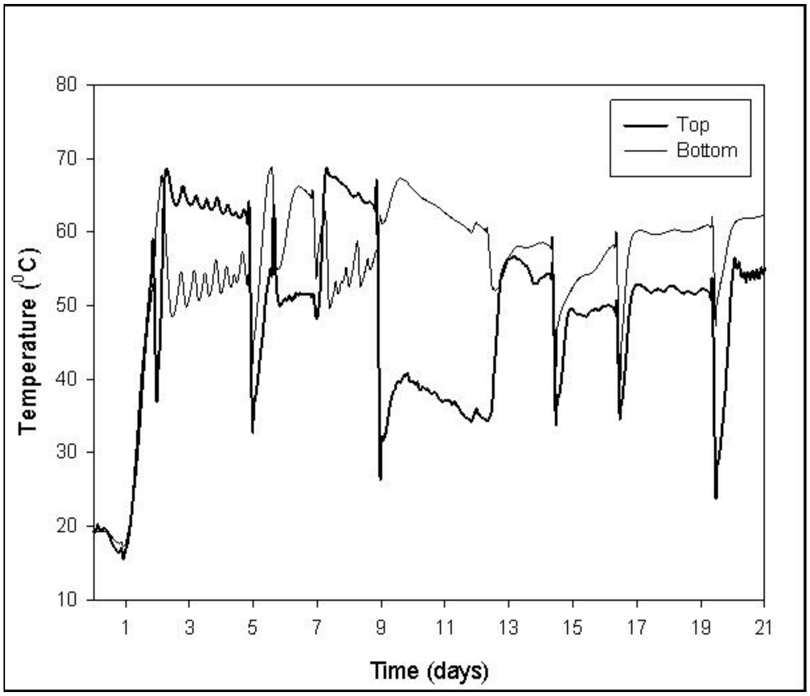


Figure B-1 Temperature profile during the 21 day composting process in the control.

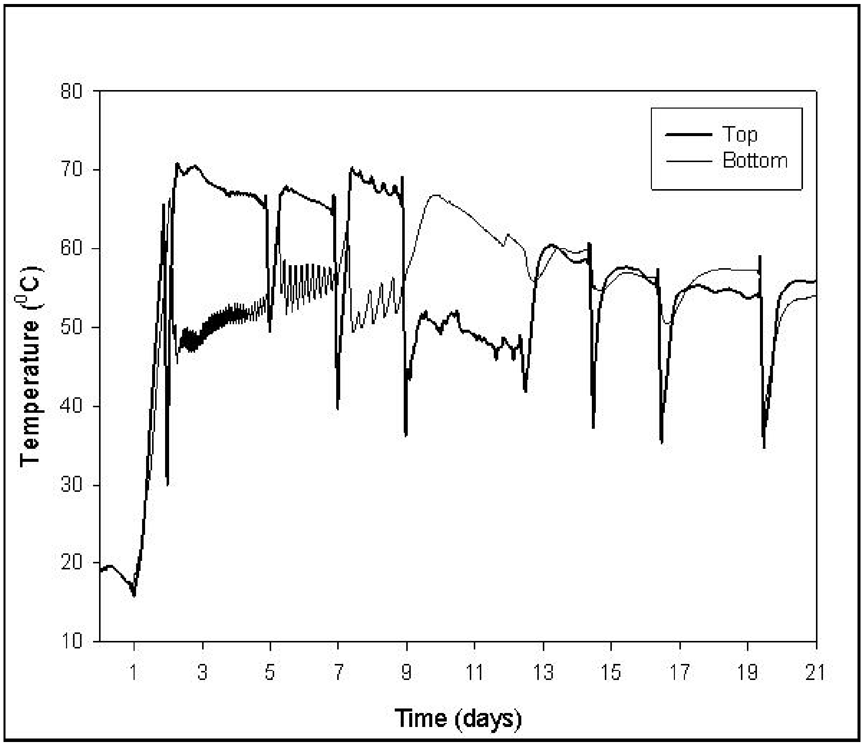


Figure B-2 Temperature profile during the 21 day composting process in the treatment of high quality batteries.

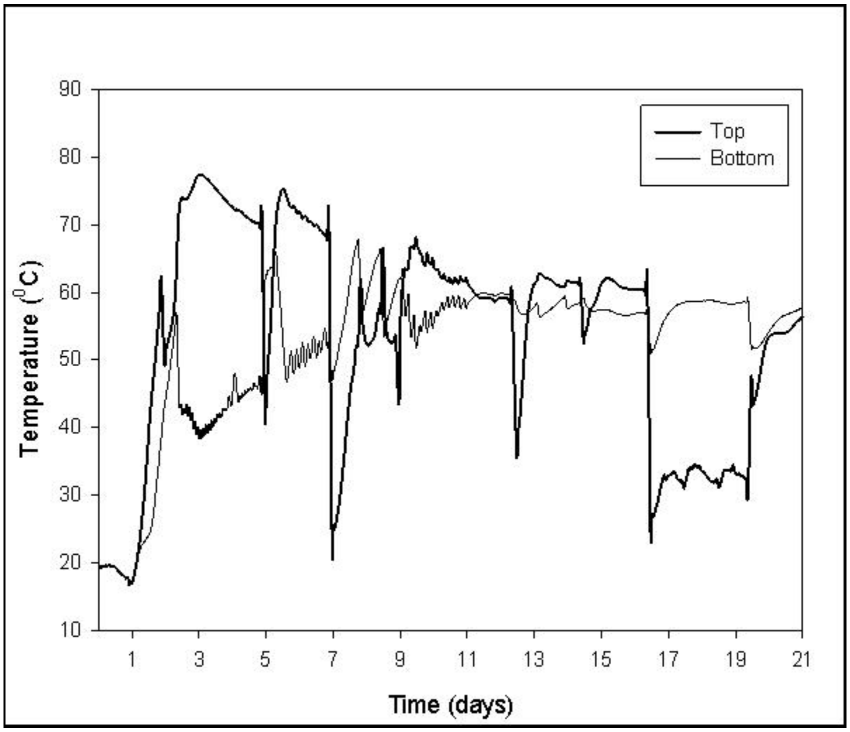


Figure B-3 Temperature profile during the 21 day composting process in the treatment of low quality batteries.

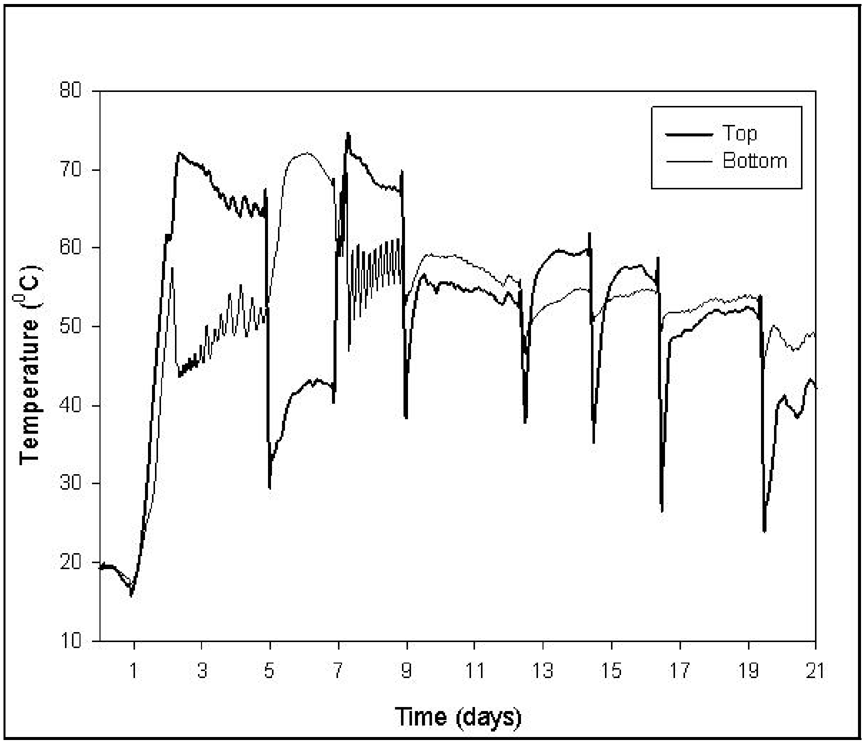


Figure B-4 Temperature profile during the 21 day composting process in the treatment of galvanized nails.

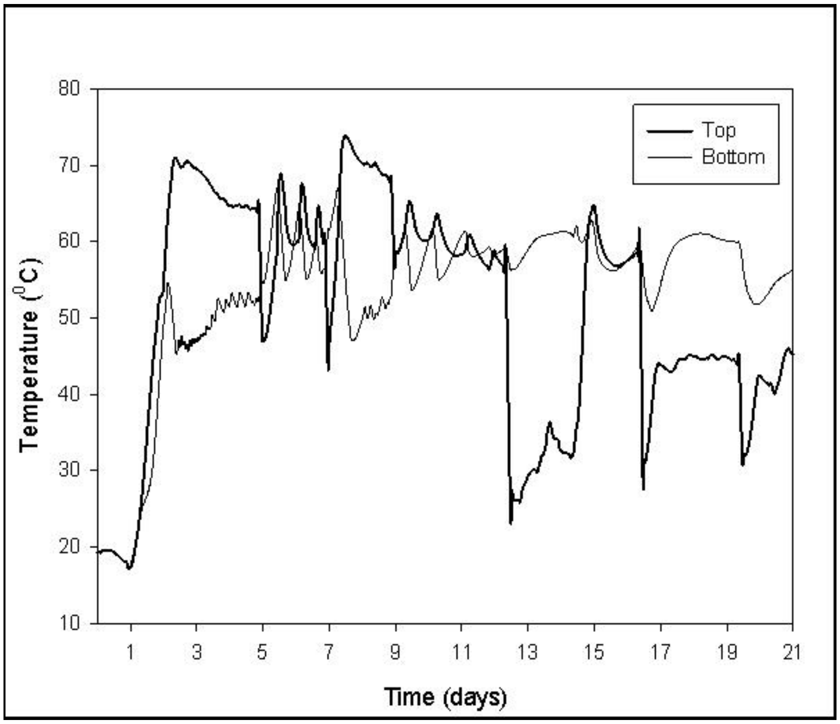


Figure B-5 Temperature profile during the 21 day composting process in the treatment of Zn-plated screws.

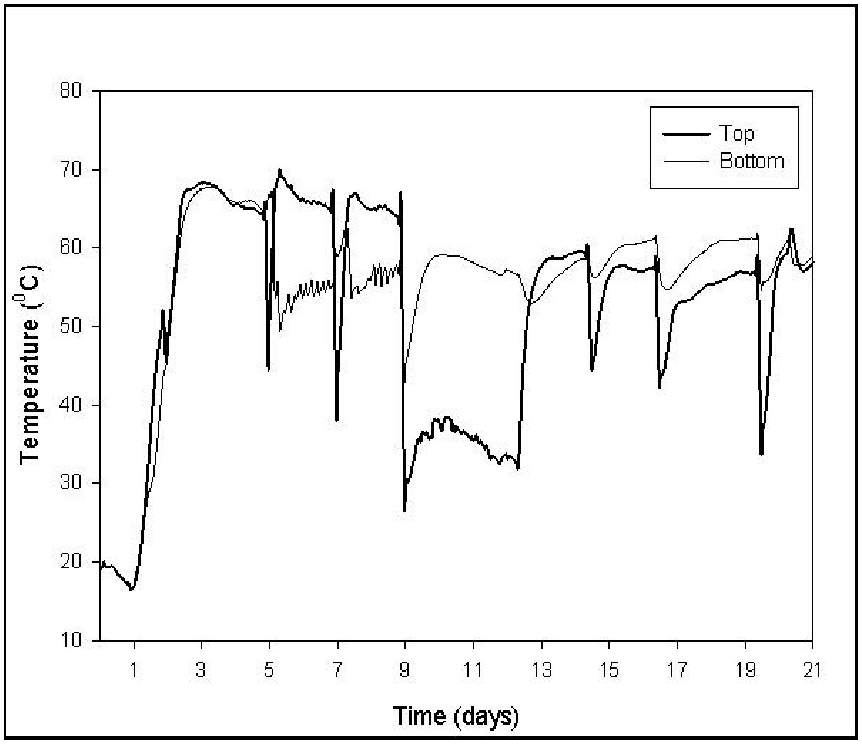


Figure B-6 Temperature profile during the 21 day composting process in the treatment of copper wires.

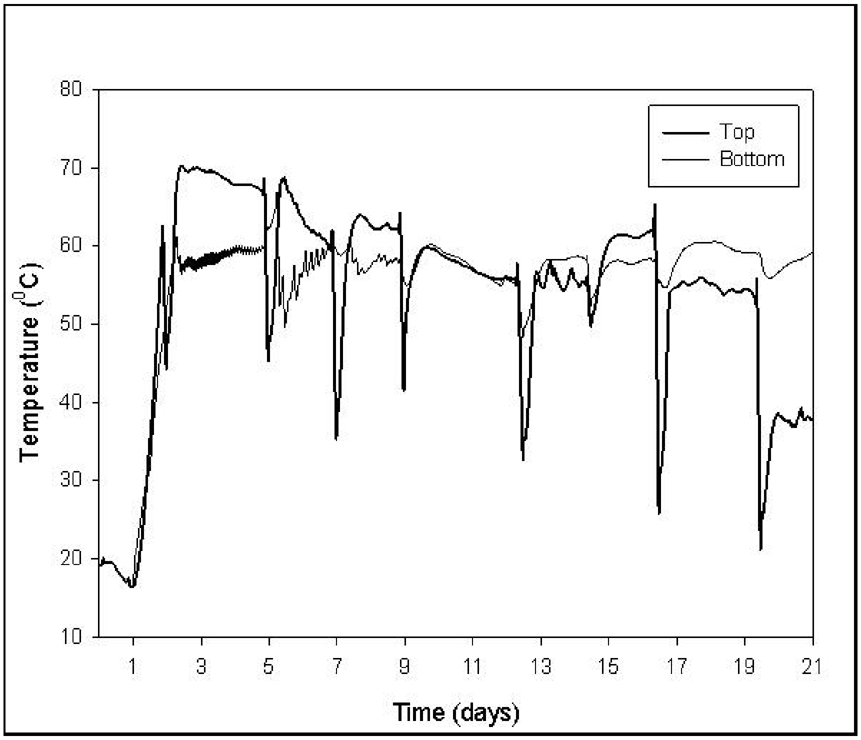


Figure B-7 Temperature profile during the 21 day composting process in the treatment of electronic cables.

B.2 Raw Data for pH and EC Values

The substrate pH and EC values are presented in Table B-1 and Table B-2. Each measurement was performed in duplicate.

Table B-1 Raw data for pH values of composting substrate in each treatment.

Time	copper wires	electronic cables	control	galvanized nails	Zn-plated screws	low-quality batteries	high-quality batteries
August 14 2009	7.06	5.89	6.02	6.86	7.1	7.15	7.22
	7.13	5.99	6.62	6.98	7.1	7.2	7.24
August 17 2009	7.2	7.36	6.68	7.43	7.95	8.02	7.95
	7.26	7.26	6.87	8.03	7.98	8.18	7.85
August 19 2009	6.79	4.82	7.26	7.09	6.55	5.79	7.91
	6.44	5.78	7.76	7.83	7.63	6.35	8.01
August 21 2009	5.24	4.92	6.12	5.81	7.34	6.00	5.75
	5.08	5.68	6.78	5.82	6.34	6.76	5.58
August 24 2009	5.12	5.24	5.34	5.17	6.78	7.68	5.86
	5.19	5.04	5.02	5.25	7.51	7.51	5.89
August 26 2009	5.02	5.23	5.34	5.14	5.55	5.36	6.24
	5.97	5.13	5.05	4.95	6.11	5.05	5.38
August 28 2009	4.97	5.31	5.12	5.27	4.98	5.04	5.18
	4.88	5.01	4.96	5.07	5.22	4.89	5.36
August 31 2009	4.99	5.34	4.95	5.24	5.04	5.12	5.01
	4.89	5.07	4.88	5.19	4.79	5.03	5.26
September 3 2009	4.98	4.91	5.03	4.91	5.13	4.95	5.12
	4.9	5.07	5.07	4.76	6.45	4.89	5.04

Table B-2 Raw data for EC (ms/cm) values of composting substrate in each treatment.

Time	copper wires	electronic cables	control	galvanized nails	Zn-plated screws	low-quality batteries	high-quality batteries
August 14 2009	2.795	2.575	2.616	3.511	2.941	2.787	3.892
	3.118	2.508	3.416	3.589	3.775	3.445	3.571
August 17 2009	2.556	2.493	2.578	3.284	3.669	2.726	3.429
	1.934	2.839	3.378	3.038	3.613	2.740	4.362
August 19 2009	3.171	3.687	3.675	3.800	3.448	3.665	4.308
	2.873	3.419	3.702	3.880	2.833	3.836	4.138
August 21 2009	3.567	3.935	3.405	3.651	4.498	3.779	3.258
	3.823	3.810	3.328	3.759	4.794	3.861	3.857
August 24 2009	3.590	4.251	3.368	4.017	4.372	4.519	3.873
	3.504	4.372	3.224	4.323	4.166	4.472	4.722
August 26 2009	3.353	3.157	4.011	3.871	3.479	3.272	3.836
	3.963	3.364	3.686	4.282	3.603	3.457	4.066
August 28 2009	4.005	3.699	3.774	4.300	4.013	3.865	5.180
	3.410	3.694	3.573	4.024	4.229	3.749	5.360
August 31 2009	2.853	4.015	4.149	4.154	4.071	4.215	4.256
	3.815	3.872	4.064	3.912	3.889	4.680	4.135
September 3 2009	3.639	3.523	3.489	4.015	4.102	3.494	4.019
	3.358	3.213	3.466	3.867	3.808	4.031	3.951

B.3 Raw Data for Other Monitored Parameters

The substrate moisture content, oxygen content and the height were measured at each turning event. The raw data is presented in Table B-3 to Table B-5.

Table B-3 The substrate moisture content (%) in all treatments.

Time	copper wires	electronic cables	control	galvanized nails	Zn-plated screws	low-quality batteries	high-quality batteries
August 14	69.3	70.6	67.5	69.9	68.6	79.8	73.4
August 17	72.5	75.7	74.8	79.7	72.8	73.0	69.0
August 19	68.7	69.7	67.3	59.9	67.1	66.3	66.3
August 21	68.2	50.1	73.9	43.6	56.8	38.2	59.8
August 24	68.8	54.4	61.0	60.4	64.1	67.3	67.5
August 26	67.4	55.5	66.2	69.5	73.3	73.0	67.5
August 28	67.9	56.0	56.6	56.9	67.9	61.1	67.8
August 31	64.8	62.5	61.7	57.2	57.0	54.4	63.3
September 3	62.4	62.4	54.4	53.7	65.0	65.0	63.2

Table B-4 The oxygen content (%) in the composting substrate in all treatments.

Time	copper wires	electronic cables	control	galvanized nails	Zn-plated screws	low-quality batteries	high-quality batteries
August 14	10	11	10	7	11	10	11
August 17	12	14	13	13	12	13	14
August 19	11	10	10	7	11	12	15
August 21	8	10	10	11	10	12	11
August 24	9	10	9	11	10	10	11
August 26	11	10	10	9	11	10	12
August 28	10	9	8	12	11	10	10
August 31	8	9	10	8	10	10	9
September 3	10	7	8	10	8	6	7

Table B-5 The height (cm) of the compost pile in all treatments before each turning event.

Time	copper wires	electronic cables	control	galvanized nails	Zn-plated screws	low-quality batteries	high-quality batteries
August 14	85	99	100	95	97	107	95
August 17	79	82	82	87	91	85	79
August 19	69	80	73	66	95	80	90
August 21	69	74	62	69	79	76	69
August 24	62	58	59	61	65	80	75
August 26	76	67	62	62	67	62	65
August 28	60	52	52	52	59	62	62
August 31	58	57	49	55	55	62	58
September 3	55	54	47	55	54	65	55

B.4 Raw Data for Specimen Weight Losses

The specimen weight loss indicated the difference between the initial weight and the weight after being exposed to a three weeks composting environment at 55-70^{o}C. The values (after chemical cleaning) for all replicates of each type of specimen were shown in Figure B-8.

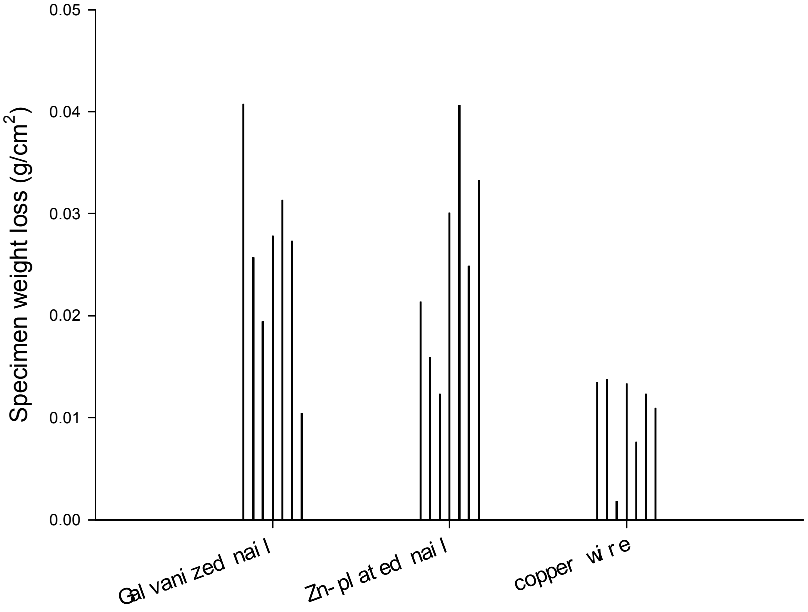


Figure B-8 Specimen weight loss (g cm^{-2}) (after chemical cleaning) after the 21 days composting process.

B.5 Concentrations for Analyzed Elements in Feedstock Materials and Composts

In total, twenty two elements including Al, As, B, Ca, Cd, Co, Cr, Cu, Fe, Hg, K, Mg, Mo, Ni, P, Pb, S, Se, Si, Ti, V, and Zn were examined in all feedstock materials and the composts after the three weeks composting process. All tests were conducted in the Alberta Research Council. The results are presented in Table B-6 to Table B-9.

Table B-6 Element concentrations (mg kg^{-1} dry weight) in feedstock materials and peat moss.

	Alfafa Hay		**Straw**		**Peat moss**	
	Replicate1	Replicate2	Replicate1	Replicate2	Replicate1	Replicate2
Al	1773	3247	276	239	2543	2182
As	0.382	0.997	0.0844	0.0657	1.27	1.32
B	33.1	32.7	3.10	3.05	10.1	9.27
Ca	17539	21384	3221	3345	11224	11317
Cd	0.125	0.136	0.158	0.146	0.167	0.159
Co	0.537	1.14	0.212	0.108	1.28	1.17
Cr	4.03	8.63	4.84	3.84	3.08	2.73
Cu	9.67	11.6	6.28	5.54	4.07	3.97
Fe	1162	5404	432	621	3774	3974
Hg	0.0265	0.0653	0.0272	0.0245	0.0493	0.0510
K	34067	22551	15906	15318	1128	801
Mg	3270	3266	780	796	1313	1227
Mo	4.42	5.05	0.572	0.507	0.681	0.662
Ni	3.29	5.17	2.08	1.83	2.30	2.22
P	2472	2236	736	710	511	516
Pb	1.76	2.43	0.894	0.606	1.69	1.59
S	3426	3596	880	1013	8045	8453
Se	0.376	0.414	< 0.1	< 0.1	0.441	0.450
Si	9519	13900	10484	10330	8085	7596
Ti	63.5	118	20.0	19.2	142	124
V	4.73	11.7	0.590	0.467	5.07	4.66
Zn	241	352	12.8	13.4	26.4	26.1

Table B-7 Element concentrations (mg kg^{-1} dry weight) in composts from treatments of control, high quality batteries and low quality batteries.

	Control		**Treatment with high quality batteries**		**Treatment with low quality batteries**	
	Replicate1	Replicate2	Replicate1	Replicate2	Replicate1	Replicate2
Al	2192.11	2656.43	1403.17	1582.40	0.00	3519.06
As	0.45	0.72	0.41	0.46	1.55	1.59
B	13.01	13.44	12.29	14.69	21.25	13.49
Ca	10203.27	12022.83	9605.72	11046.97	18747.65	11163.25
Cd	0.13	0.14	0.10	0.11	0.18	0.13
Co	0.55	0.67	0.48	0.56	1.58	1.10
Cr	4.74	5.39	2.90	3.48	9.36	34.41
Cu	7.73	8.26	5.10	6.05	22.38	33.43
Fe	1520.53	1863.44	1269.81	1222.13	4926.66	3870.97
Hg	0.03	0.03	0.02	0.02	0.06	0.22
K	17875.65	17079.89	13915.73	15326.43	24257.24	14389.05
Mg	2092.47	2105.47	1855.43	1922.77	4381.35	1902.25
Mo	1.70	1.63	1.53	1.57	3.70	9.42
Ni	3.33	3.84	3.02	3.56	8.14	15.70
P	1554.40	1733.57	1034.02	1148.49	2237.68	1532.75
Pb	1.64	2.05	1.35	1.68	6.07	3.48
S	2032.68	2164.50	1538.46	1982.48	2444.53	1587.49
Se	< 0.1	< 0.1	< 0.1	< 0.1	0.33	0.19
Si	11259.47	16036.99	10127.56	13913.22	22940.96	16070.38
Ti	73.73	97.99	64.94	79.42	208.73	105.77
V	4.03	5.35	4.16	4.40	14.25	10.95
Zn	57.39	58.84	66.87	76.04	139.71	117.11

Table B-8 Element concentrations (mg kg^{-1} dry weight) in composts from treatments of galvanized nails and Zn-plated screws.

	Treatment with galvanized nails		**Treatment with Zn-plated screws**	
	Replicate1	Replicate2	Replicate1	Replicate2
Al	1644.65	1965.63	1281.19	1400.35
As	0.46	0.46	0.33	0.46
B	9.02	10.08	9.86	12.24
Ca	7274.42	8297.12	7447.44	9270.49
Cd	0.08	0.10	0.09	0.09
Co	0.52	0.56	0.37	0.50
Cr	13.62	3.85	2.67	3.64
Cu	4.69	5.65	4.19	5.22
Fe	1216.74	1286.05	1078.80	1288.87
Hg	0.11	0.02	0.02	0.02
K	9841.86	13235.88	12556.49	13436.34
Mg	1237.21	1406.56	1465.91	1738.71
Mo	4.54	1.36	1.12	1.30
Ni	6.07	2.88	1.92	2.48
P	883.72	1122.09	951.07	1136.32
Pb	1.27	2.00	1.05	1.25
S	1447.44	1321.61	1011.99	1371.02
Se	0.10	0.16	< 0.1	< 0.1
Si	10827.91	10924.54	8646.10	11871.70
Ti	69.02	79.22	49.72	74.91
V	5.40	4.03	2.93	3.97
Zn	219.53	310.15	96.09	115.00

Table B-9 Element concentrations (mg kg^{-1} dry weight) in composts from treatments of copper wires and electronic cables.

	Treatment with copper wires		**Treatment with electronic cables**	
	Replicate1	Replicate2	Replicate1	Replicate2
Al	2665.64	3226.44	2397.33	1985.84
As	0.46	0.79	0.69	0.49
B	8.81	9.19	8.51	8.45
Ca	7726.48	12104.03	7133.03	7176.56
Cd	0.09	0.12	0.09	0.09
Co	0.55	0.85	0.58	0.48
Cr	3.98	10.75	6.15	3.89
Cu	204.75	226.83	16.88	15.22
Fe	1446.78	1937.82	1625.07	1596.54
Hg	0.02	0.07	0.03	0.02
K	13714.51	13140.40	12438.59	13035.78
Mg	1271.01	1308.17	1167.22	1185.61
Mo	1.13	3.11	1.49	1.18
Ni	3.05	5.87	3.54	3.34
P	1178.29	1261.24	1155.43	1132.52
Pb	1.40	2.17	1.76	1.63
S	1245.90	1272.98	1208.49	1224.93
Se	0.11	0.18	0.14	0.10
Si	9870.58	14489.64	11770.49	10735.35
Ti	84.80	120.45	82.53	72.75
V	3.98	6.84	6.82	4.21
Zn	54.47	59.84	56.00	60.95

APPENDIX C STATISTICAL ANALYSIS OF AXPERIMENTAL DATA (TRIAL 1)

C.1 Results of Statistical Analysis Regarding Specimen Weight Loss

The effects of the degree of acidity on specimen weight loss were examined by using t-tests (two groups). The tests were carried out using Sigma Plot 11.0. The results for the six types of contaminants are presented below.

(1) Data source: Galvanized nails

```
Normality Test:        Passed (P = 0.119)
Equal Variance Test:         Passed (P = 0.187)

Group Name             N    Missing    Mean     Std Dev     SEM
Galvanized nails(Hp)    7      0        0.0112   0.00407   0.00154
Galvanized nails(Lp)  10      0        0.0300   0.00711   0.00225

Difference      -0.0188

t = -6.266  with 15 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: -0.0252 to -0.0124

The difference in the mean values of the two groups is greater than would be expected by
chance; there is a statistically significant difference between the input groups (P =
<0.001).

Power of performed test with alpha = 0.050: 1.000
```

(2) Data source: Zn-plated screws

Normality Test: Passed (P = 0.191)
Equal Variance Test: Passed (P = 0.100)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Zn-plated screws (Hp)	8	0	0.0125	0.00475	0.00168
Zn-plated screws (Lp)	9	0	0.0281	0.0124	0.00413

Difference -0.0156

t = -3.344 with 15 degrees of freedom. (P = 0.004)

95 percent confidence interval for difference of means: -0.0256 to -0.00566

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = 0.004).

Power of performed test with alpha = 0.050: 0.860

(3) Data source: Stainless steel flat washer

Normality Test: Passed (P = 0.496)

Equal Variance Test: Passed (P = 0.847)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Stainless steel flat washer (Hp)	8	0	0.000228	0.0000466	0.0000165
Stainless steel flat washer (Lp)	9	0	0.000295	0.0000301	0.0000100

Difference -0.0000672

t = -3.578 with 15 degrees of freedom. (P = 0.003)

95 percent confidence interval for difference of means: -0.000107 to -0.0000272

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = 0.003).

Power of performed test with alpha = 0.050: 0.909

(4) Data source: Copper wires

Normality Test: Passed (P = 0.072)

Equal Variance Test: Passed (P = 0.075)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Copper wires(Hp)	9	0	0.00141	0.000817	0.000272
Copper wires(Lp)	8	0	0.00850	0.00252	0.000892

Difference -0.00709

t = -8.003 with 15 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: -0.00898 to -0.00520

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

(5) Data source: Brass screws

Normality Test: Passed (P = 0.501)

Equal Variance Test: Failed (P < 0.050)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Brass screws (Hp)	9	0	0.00252	0.000615	0.000205
Brass screws (Lp)	9	0	0.0146	0.00385	0.00128

Difference -0.0121

t = -9.275 with 16 degrees of freedom. (P = <0.001)

95 percent confidence interval for difference of means: -0.0148 to -0.00931

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = <0.001).

Power of performed test with alpha = 0.050: 1.000

(6) Data source: Light bulb tail contact

Normality Test: Passed (P = 0.261)

Equal Variance Test: Passed (P = 0.281)

Group Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
Light bulb tail contact (Hp)	4	0	0.00866	0.00221	0.00111
Light bulb tail contact (Lp)	8	0	0.0164	0.00607	0.00215

Difference -0.00772

t = -2.414 with 10 degrees of freedom. (P = 0.036)

95 percent confidence interval for difference of means: -0.0148 to -0.000594

The difference in the mean values of the two groups is greater than would be expected by chance; there is a statistically significant difference between the input groups (P = 0.036).

Power of performed test with alpha = 0.050: 0.504

APPENDIX D STATISTICAL ANALYSIS OF EXPERIMENTAL DATA (TRIAL 2)

D.1 Results of Statistical Analyses Regarding Trace Metal Concentrations in Composts

The effects of different contaminants on the tracer metal content of compost were determined by using one-way ANOVA analyses (one factor). The differences in concentrations of eleven trace metals were evaluated among all of the seven treatments. For trace metals which showed significant differences in concentrations among all treatments, the Holm-Sidak test was carried out to compare the differences between each treatment and the control. The results are presented below.

One Way Repeated Measures Analysis of Variance

(1) Data source: As

Normality Test: Passed (P = 0.771)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	0.581	0.191	0.135
high quality battery	2	0	0.437	0.0354	0.0250
low quality battery	2	0	1.567	0.0296	0.0209
galvanized nail	2	0	0.458	0.000424	0.000300
Zn-plated screw	2	0	0.394	0.0874	0.0618
copper wire	2	0	0.626	0.235	0.166
electrical cable	2	0	0.587	0.143	0.101

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	0.0189	0.0189		
Between Treatments	6	1.992	0.332	19.359	**0.001**
Residual	6	0.103	0.0171		
Total	13	2.114			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.001). To isolate the group or groups that differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.050: 0.999

Multiple Comparisons versus Control Group (Holm-Sidak method):

Overall significance level = 0.05
Comparisons for factor:

Comparison	Diff of Means	t	Unadjusted P	Critical Level	Significant?
control vs. low quality	0.985	7.524	<0.001	0.009	Yes
control vs. Zn-plated screw	0.187	1.431	0.202	0.010	No
control vs. high quality	0.145	1.104	0.312	0.013	No
control vs. galvanized nail	0.123	0.942	0.383	0.017	No
control vs. copper wire	0.0444	0.339	0.746	0.025	No
control vs. electrical cable	0.00535	0.0409	0.969	0.050	No

(2) Data source: Cd

Normality Test: Passed (P = 0.329)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	0.136	0.00778	0.00550
high quality battery	2	0	0.107	0.0110	0.00775
low quality battery	2	0	0.151	0.0351	0.0248
galvanized nail	2	0	0.0861	0.0135	0.00955
Zn-plated screw	2	0	0.0912	0.00417	0.00295
copper wire	2	0	0.106	0.0254	0.0179
electrical cable	2	0	0.0921	0.00410	0.00290

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	0.000135	0.000135		
Between Treatments	6	0.00726	0.00121	3.390	0.082
Residual	6	0.00214	0.000357		
Total	13	0.00954			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.082).

Power of performed test with alpha = 0.050: 0.405

The power of the performed test (0.405) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(3) Data source: Co

Normality Test: Passed (P = 0.841)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	0.608	0.0870	0.0615
high quality battery	2	0	0.516	0.0578	0.0409
low quality battery	2	0	1.344	0.338	0.239
galvanized nail	2	0	0.537	0.0255	0.0180
Zn-plated screw	2	0	0.437	0.0928	0.0656
copper wire	2	0	0.704	0.211	0.149
electrical cable	2	0	0.532	0.0706	0.0499

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	0.000599	0.000599		
Between Treatments	6	1.148	0.191	6.252	0.021
Residual	6	0.184	0.0306		
Total	13	1.332			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.021). To isolate the group or groups that differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.050: 0.759

Multiple Comparisons versus Control Group (Holm-Sidak method):

Overall significance level = 0.05
Comparisons for factor:

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
control vs. low quality	0.736	4.210	0.006	0.009	Yes
control vs. Zn-plated screw	0.170	0.975	0.367	0.010	No
control vs. copper wire	0.0960	0.549	0.603	0.013	No
control vs. high quality	0.0911	0.521	0.621	0.017	No
control vs. electrical cable	0.0759	0.434	0.680	0.025	No
control vs. galvanized nail	0.0704	0.402	0.701	0.050	No

(4) Data source: Cr

Normality Test: Passed (P = 0.565)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	5.067	0.459	0.324
high quality battery	2	0	3.191	0.413	0.292
low quality battery	2	0	21.886	17.709	12.522
galvanized nail	2	0	8.735	6.906	4.883
Zn-plated screw	2	0	3.155	0.683	0.483
copper wire	2	0	7.367	4.791	3.388
electrical cable	2	0	5.022	1.596	1.129

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	34.554	34.554		
Between Treatments	6	514.981	85.830	1.458	0.329
Residual	6	353.094	58.849		
Total	13	902.628			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.329).

Power of performed test with alpha = 0.050: 0.106

The power of the performed test (0.106) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(5) Data source: Cu

Normality Test: Passed (P = 0.363)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	7.998	0.376	0.266
high quality battery	2	0	5.577	0.671	0.474
low quality battery	2	0	27.904	7.817	5.527
galvanized nail	2	0	5.169	0.680	0.481
Zn-plated screw	2	0	4.704	0.733	0.518
copper wire	2	0	215.790	15.610	11.038
electrical cable	2	0	16.049	1.175	0.831

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	87.242	87.242		
Between Treatments	6	72577.484	12096.247	329.129	<0.001
Residual	6	220.513	36.752		
Total	13	72885.239			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = <0.001). To isolate the group or groups that differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.050: 1.000

Multiple Comparisons versus Control Group (Holm-Sidak method):

Overall significance level = 0.05
Comparisons for factor:

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
control vs. copper wire	207.792	34.276	<0.001	0.009	Yes
control vs. low quality	19.906	3.283	0.017	0.010	No
control vs. electrical cable	8.051	1.328	0.232	0.013	No
control vs. Zn-plated screw	3.295	0.543	0.606	0.017	No
control vs. galvanized nail	2.829	0.467	0.657	0.025	No
control vs. high quality	2.422	0.399	0.703	0.050	No

(6) Data source: Hg

Normality Test: Passed (P = 0.208)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	N	Missing	Mean	Std Dev	SEM
control	2	0	0.0285	0.000566	0.000400
high quality battery	2	0	0.0214	0.00269	0.00190
low quality battery	2	0	0.143	0.116	0.0822
galvanized nail	2	0	0.0648	0.0586	0.0415
Zn-plated screw	2	0	0.0166	0.00163	0.00115
Zn-plated screw	2	0	0.0166	0.00163	0.00115
copper wire	2	0	0.0461	0.0360	0.0254
electrical cable	2	0	0.0221	0.00856	0.00605

Source of Variation	DF	SS	MS	F	P
Between Subjects	1	0.00105	0.00105		
Between Treatments	7	0.0258	0.00368	1.492	0.305
Residual	7	0.0173	0.00247		
Total	15	0.0441			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.305).

Power of performed test with alpha = 0.050: 0.119

The power of the performed test (0.119) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(7) Data source: Mo

Normality Test: Passed (P = 0.548)

Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	1.665	0.0472	0.0333
high quality battery	2	0	1.551	0.0226	0.0160
low quality battery	2	0	6.564	4.044	2.859
galvanized nail	2	0	2.949	2.249	1.590
Zn-plated screw	2	0	1.208	0.125	0.0883
copper wire	2	0	2.120	1.398	0.989
electrical cable	2	0	1.335	0.216	0.153

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	1.353	1.353		
Between Treatments	6	42.970	7.162	1.946	0.219
Residual	6	22.077	3.680		
Total	13	66.400			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.219).

Power of performed test with alpha = 0.050: 0.176

The power of the performed test (0.176) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(8) Data source: Ni

Normality Test: Passed (P = 0.623)

Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	3.583	0.360	0.255
high quality battery	2	0	3.289	0.387	0.274
low quality battery	2	0	11.921	5.343	3.778
galvanized nail	2	0	4.475	2.249	1.590
Zn-plated screw	2	0	2.201	0.400	0.283
copper wire	2	0	4.459	1.990	1.407
electrical cable	2	0	3.440	0.138	0.0973

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	5.305	5.305		
Between Treatments	6	126.575	21.096	3.868	0.062
Residual	6	32.724	5.454		
Total	13	164.604			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.062).

Power of performed test with alpha = 0.050: 0.478

The power of the performed test (0.478) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(9) Data source: Pb

Normality Test: Passed (P = 0.269)

Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	1.845	0.284	0.201
high quality battery	2	0	1.514	0.228	0.162
low quality battery	2	0	4.777	1.834	1.297
galvanized nail	2	0	1.632	0.514	0.363
Zn-plated screw	2	0	1.149	0.140	0.0993
copper wire	2	0	1.786	0.543	0.384
electrical cable	2	0	1.697	0.0924	0.0654

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	0.00668	0.00668		
Between Treatments	6	17.891	2.982	4.388	0.047
Residual	6	4.077	0.680		
Total	13	21.974			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.047). To isolate the group or groups that differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.050: 0.552

Multiple Comparisons versus Control Group (Holm-Sidak method):

Overall significance level = 0.05
Comparisons for factor:

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
control vs. low quality	2.932	3.556	0.012	0.009	No
control vs. Zn-plated screw	0.697	0.845	0.430	0.010	No
control vs. high quality	0.331	0.401	0.702	0.013	No
control vs. galvanized nail	0.213	0.259	0.805	0.017	No
control vs. electrical cable	0.148	0.180	0.863	0.025	No
control vs. copper wire	0.0588	0.0713	0.945	0.050	No

(10) Data source: Se

Normality Test: Passed (P = 0.927)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	0.1000	0.000	0.000
high quality battery	2	0	0.1000	0.000	0.000
low quality battery	2	0	0.260	0.106	0.0747
galvanized nail	2	0	0.128	0.0397	0.0280
Zn-plated screw	2	0	0.1000	0.000	0.000
copper wire	2	0	0.147	0.0469	0.0331
electrical cable	2	0	0.123	0.0303	0.0214

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	0.000349	0.000349		
Between Treatments	6	0.0392	0.00654	2.531	0.142
Residual	6	0.0155	0.00258		
Total	13	0.0551			

The differences in the mean values among the treatment groups are not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.142).

Power of performed test with alpha = 0.050: 0.268

The power of the performed test (0.268) is below the desired power of 0.800.
Less than desired power indicates you are less likely to detect a difference when one actually exists. Negative results should be interpreted cautiously.

(11) Data source: Zn

Normality Test: Passed (P = 0.283)
Equal Variance Test: Failed (P < 0.050)

Treatment Name	**N**	**Missing**	**Mean**	**Std Dev**	**SEM**
control	2	0	58.114	1.019	0.721
high quality battery	2	0	71.454	6.479	4.581
low quality battery	2	0	128.410	15.986	11.304
galvanized nail	2	0	264.845	64.077	45.310
Zn-plated screw	2	0	105.545	13.372	9.456
copper wire	2	0	57.154	3.793	2.682
electrical cable	2	0	58.477	3.499	2.474

Source of Variation	**DF**	**SS**	**MS**	**F**	**P**
Between Subjects	1	830.667	830.667		
Between Treatments	6	67728.556	11288.093	17.921	0.001
Residual	6	3779.267	629.878		
Total	13	72338.491			

The differences in the mean values among the treatment groups are greater than would be expected by chance; there is a statistically significant difference (P = 0.001). To isolate the group or groups that differ from the others use a multiple comparison procedure.

Power of performed test with alpha = 0.050: 0.998

Multiple Comparisons versus Control Group (Holm-Sidak method):

Overall significance level = 0.05
Comparisons for factor:

Comparison	**Diff of Means**	**t**	**Unadjusted P**	**Critical Level**	**Significant?**
control vs. galvanized nail	206.730	8.237	<0.001	0.009	Yes
control vs. low quality	70.296	2.801	0.031	0.010	No
control vs. Zn-plated screw	47.431	1.890	0.108	0.013	No
control vs. high quality	13.340	0.532	0.614	0.017	No
control vs. copper wire	0.961	0.0383	0.971	0.025	No
control vs. electrical cable	0.363	0.0145	0.989	0.050	No

APPENDIX E COMPOSITION OF EDMONTON MUNICIPAL SOLID WASTE

The composition of Edmonton MSW is presented in Table E-1. The numbers in bold were used in the experimental design in the second trial of the experiment.

Table E-1 Edmonton MSW composition (weight percentage) (City of Edmonton 2003).

Category	Material	% of total MSW[b], (wet basis)
1	Paper	16.5
2	Food	23.3
3	Other organics	9.0
	Diapers	4.2
	Land clearing debris	0.0
	Lumber & wood	1.8
	Rubber products	0.2
	Other Misc. organics	2.8
4	Yard waste	28.9
5	Metal	2.6
	Soft drink	0.3
	Food & beverage containers (Fe)	1.0
	Aerosol cans	0.06
	Mixed metals & materials	**0.65**
	Other	**0.57**
6	Aluminum	0.6
	Food & beverage containers (Al)	0.2
	Other non-ferrous	0.4
7	Glass	2.1
8	Plastics	7.1
9	Textiles & leather products	2.8
10	Other wastes	6.0
	Inert solids	0.4
	Brown goods[a]	0.7
	Construction/demolition/carpet	1.7
	Pharmaceuticals/cosmetics	0.3
	Fines	2.9
11	HHW	1.0
	Latex paint products	0.44
	Adhesive/glues/sealants	0.03
	Cleaners	0.05
	Solvents/Oil-based paints	0.23
	Pesticides/herbicides	0.05
	Lead-acid batteries	0.00
	Other batteries	**0.08**
	Gasoline/explosive	0.00
	Engine oil	0.06
	Asbestos	0.00
	Sharps	0.00
	Other	0.08
	Total	100.0%

Notes: [a] Brown Goods: Household electrical entertainment appliances (CD Players, TVs, camcorders etc.).
[b] Total MSW received at ECF in 2001: 177,010 tonnes.

APPENDIX F CALCULATIONS OF EXPERIMENTAL DATA

F.1 Calculation of Contaminant Metal Transfer

The determination of contaminant metal transfer (Table 3-6) was based on the weight ratio of the trace metal and the tested specimen weight loss value. An example for copper wire is illustrated as follow:

1) The average weight loss for the tested copper wire (25 mm in length) in the Lp treatment is 0.008 g cm^{-2}.

2) Surface area (A) of each specimen:

$A = \text{Length} \times \pi D = 2.5\ cm \times 3.14 \times 0.2\ cm = 1.57 cm^2$

3) Weight of the specimen: 0.7856 g

4) Mass transfer from the specimen: $0.008\ g\ cm^{-2} \times 1.57cm^2 \div 0.7856\ g = 0.0159\ g\ g^{-1}$

According to the SEM-EDX analysis, the surface of the tested copper wire contains 100% of copper. Thus,

Mass of copper transferred: $100\% \times 0.0159\ g\ g^{-1} = 0.0159\ g\ g^{-1}$

The maximum disposal of the tested copper wire was calculated based on the CCME Category A limit for copper.

Maximum disposal of the tested copper wire = CCME A Limit $\div$ mass transfer of copper = $400\ mg\ kg^{-1}$ dry compost $\div 0.0159\ g\ g^{-1} \times 10^{-3}\ g\ mg^{-1}$

= $25.12\ g\ kg^{-1}$ dry compost

Weight of each tested copper wire (25 mm in length) is 0.7856 g. The number of the copper wire can be disposed = $25.12\ g\ kg^{-1}$ dry compost $\div 0.7856\ g = 32$

F.2 Calculation of the Predicted and Observed Metal Increase in Compost

The predicted metal increase in compost was calculated based on the contaminant added to each treatment and the metal mass transfer of each type of contaminant. An example for copper wire is illustrated as follow:

1) The mass transfer of copper from copper wire is 0.0114g g^{-1}.
2) The total addition for copper wire to 100 kg feedstock (ww) is 1220 g.
3) The total mass transfer of copper = 1220 g × 0.0114g g^{-1} = 13.908 g
4) The height of compost is 55 cm at the end of the process. Moisture content is 62.4%. Bulk density is 265.9 kg m^{-3}. Diameter of the bioreactor is 1 m.
   The mass of final compost (dry weight) = Volume of compost × Bulk density × (1-moisture content) = $1^2 \times \pi \div 4 \times 0.55$ m × 265.9 kg m^{-3} × (1-62.4%) = 43.14 kg dry compost
5) Predicted increase of copper = total mass transfer of copper ÷ mass of compost (dry weight) = 13.908 g ÷ 43.14 kg dry compost = 322.38 mg kg^{-1} dry compost

The observed metal increase in compost = Observed copper content in the treatment of copper wire – Observed copper content in the treatment of control = 215.79 mg kg^{-1} dry compost -8.00 mg kg^{-1} dry compost = 207.79 mg kg^{-1} dry compost