Integration of Anaerobic Digestion and Composting Facilities

by

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ABSTRACT

Interest in organic waste treatment has increased in recent years due to growing rate of organic waste generation. Implementing biotransformation technologies helps to divert organic waste from landfill, reduce greenhouse gas emission, and produce valuable final products. This research was conducted in two parts. The general goal of the first part was to extend the overall knowledge in organic waste characterization, generation rate, sources, and sampling. While in the second part, which is the main part of the dissertation, the focus was on anaerobic digestion and composting processes and integration of these two biotransformation technologies.

In the first part (Chapter 2), a sampling methodology was proposed for higher education institutions (HEI's), as one of the main generators in institutional, commercial, and industrial (ICI) sectors. Representative organic waste was collected according to the proposed methodology and characterized in terms of their physical, chemical, and biological properties.

In the second part, different options of digestate post treatment were investigated in an integrated anaerobic digestion and composting system. Co-composting of digestate and organic fraction of municipal solid waste (OFMSW) was studied in terms of physicochemical parameters and microbial population dynamics in Chapter 3 and 4, respectively. Digestate was prepared by running a high solid anaerobic digestion (HSAD) reactor with the working volume of 500 L. Then it was mixed with OFMSW in eight different mixing ratios; 0, 10, 20, 30, 40, 50, 75, or 100% (wet mass). Composting reactors with working volume of 25 L were monitored for 100 days including 30 days of

aeration and 70 days of curing. Monitored parameters were temperature, mass changes, total solids, organic matter, pH, and electrical conductivity. Stability and maturity endpoints were also quantified by running respirometry, C:N ratio, ammonium to nitrate ratio, and Solvita® tests. The results revealed that the reactors with 20 to 40% (%ww) digestate had better performance in terms of organic matter (OM) removal, temperature evolution, and also stability time. Results also showed that total ammonia nitrogen (TAN) available in the digestate could be an effective parameter in organic matter degradation and composting performance. Concentration above 5000 TAN $mg.kg^{-1}$ DM found to be unfavorable for the biological activities where the improvement in composting performance was observed in the lower concentrations of TAN. OFMSW could also enhance the physicochemical properties of the digestate by balancing free air space, moisture content, and C:N ratio parameters. Simpson index calculated from pyrosequencing results also showed that microbial diversity was higher in the reactors with better performance. Proper mixing ratio of the digestate and OFMSW, 20 to 40%, (%ww) probably provided the most favourable condition for bacteria and fungi activities. Higher relative abundance of the two bacterial phyla, *Thermoactinomycetaceae* and *Actinomycetales*, in the reactors with 20 to 40% digestate indicated a potential of high efficient and rapid composting. In the fungal community, *Galactomyces*, *Pichia*, *Chaetomium*, and *Acremonium* were the four genera probably involved in higher OM degradation in the reactors with better performance.

In Chapter 5, co-composting of polished digestate and composted OFMSW was studied as another option for further treatment of digestate. 8-day aerated digestate was mixed with composted OFMSW in eight different mixing ratios; 0, 20, 30, 40, 50, 60, 80,

or 100% (wet mass) as feedstock for the curing process. Curing process was monitored during 100 days, with the same physicochemical analyses applied in the previous options. The results demonstrated that the two main feedstocks could not take advantages of each other and composting performance decreased when the digestate portion increased. This could be due to loss of N during aeration of the digestate and/or inappropriate inoculation time.

Overall, comparing all the investigated options demonstrated that co-composting of the digestate and OFMSW with the mixing ratio of 20 to 40% was associated with higher OM degradation, higher temperature generation, and shorter stability time. Therefore co-composting of digestate with the OFMSW is suggested as a reliable and robust method for further treatment of the digestate.

PREFACE

The research completed in this dissertation was planned, designed, conducted, analyzed, interpreted, and compiled by myself, under supervision of Dr. Daryl McCartney in the Department of Civil and Environmental Engineering at the University of Alberta.

A version of Chapter 2 of this thesis has been submitted as a case study research article of G. Arab and D. McCartney entitled "Organic Waste Characterization at Large Post-Secondary Institutions" in *Waste and Biomass Vaporization* jounal. I was responsible for experimental measurements, data analysis, and manuscript composition. Mr. Kentson Yan and Mr. Shahid Malik helped me with sample collection and preparation. This work was supported by University of Alberta, Energy Management & Sustainable Operations.

The pilot-scale composting setup referred to in Chapters 3, 4 and 5 were designed and operated by myself. Composting reactors were repaired with the assistance of Christine Heyregers. The environmental chamber was constructed by Curtis Faucher. The high solids anaerobic digestion pilot scale was operated at Alberta Innovates-Technology Futures (AI-TF).

A version of Chapter 3 of this thesis has been accepted as a research article of G. Arab and D. McCartney entitled "Benefits to Decomposition Rates When Using Digestate as Compost Feedstock: Part I - Focus on Physicochemical Parameters" in *Waste Management* journal. I was responsible for the composter reactor operation, experimental measurements, data collection, and data analysis for the manuscript composition. This work was supported by the City of Edmonton and Mitacs-Accelerate (ITO4535).

A version of Chapter 4 of this thesis has been submitted as a research article of G. Arab, V. Razaviarani, Y. Liu, Z. Sheng, and D. McCartney entitled "Benefits to Decomposition Rates When Using Digestate as Compost Feedstock: Part II - Focus on

Microbial Community Dynamics" in *Waste Management* journal. I was responsible for the composter reactor operation, data collection, and experimental measurements. DNA extraction was conducted in Dr. Yang Liu's microbiology lab with assistance of Dr. Zhiya Sheng at the University of Alberta. Dr. Vahid Razaviarani assisted me with data analysis. He also contributed in discussion section of the manuscript. This work was supported by the City of Edmonton, Edmonton Waste Management Centre of Excellence (EWMCE), and Mitacs-Accelerate (ITO4535).

A version of Chapter 5 of this thesis has been submitted as a research article of G. Arab and D. McCartney entitled "Effects of digestate co-composting on curing phase of composting" in *Waste Management* journal. I was responsible for the composter reactor operation, data collection and analysis, and experimental measurements for the manuscript composition. This work was supported by the City of Edmonton and Mitacs-Accelerate (ITO4535).

DEDICATION

I dedicate this dissertation to my beloved family, who are the world to me.

A special gratitude to my loving parents, ***Mina*** *and* ***Ali****, for their invaluable support and dedicated partnership for success throughout my life.*

A very special thanks to my lovely brother, ***Kourosh****, for his forever love, support, and encouragement.*

In spite of our long distance, you have been always with me in every step of this way, through all the good and bad times. Thank you for all the unconditional love. This journey would not have been possible without your support.

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I highly appreciate the contribution of my co-author Dr. Vahid Razaviarani. Thank you for being such a supportive friend and a great source of inspiration.

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I would also like to express my gratitude to the Edmonton Waste Management Center of Excellence (EWMCE). It was my pleasure to work at the Centre and get inspired by every single employee there. A special thanks to Kristine Wichuk and Curtis Faucher for their valuable assistance throughout the project, and more importantly for their friendship.

I would like to acknowledge the financial support received from University of Alberta (Energy Management & Sustainable Operations), City of Edmonton, EWMCE, and Mitacs-Accelerate (ITO4535).

Finally, a special thanks to my dearest family for their invaluable supports and sacrifices throughout the course of this journey.

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AI-TF	Alberta Innovates-Technology Futures
AD	Anaerobic digestion
BMP	Biochemical methane Potential
C_{bio}	Biodegradable carbon
C_{bio}:N	Biodegradable carbon to nitrogen ratio
BD	Bulk density
CCQC	California Compost Quality Council
C:N	Carbon to nitrogen ratio
CoE	City of Edmonton
C & D	Construction and Demolition
ECR	Edmonton capital region
ECF	Edmonton Composting Facility
EWMC	Edmonton Waste Management Centre
EWMCE	Edmonton Waste Management Centre of Excellence
EC	Electrical conductivity
FAS	Free air space
HSAD	High solid anaerobic digestion
HSADF	High solids anaerobic digestion facility
HEI	Higher education institution
ICI	Institutional, commercial, and industrial
IPTF	Integrated Processing and Transfer Facility
MRT	Material retention time
MC	Moisture content
OFMSW	Organic fraction of municipal solid waste
OM	Organic matter
RDA	Redundancy analysis
RHG	Relative heat generation
ROR	Relative OM removal
SSO	Source-separated organics
SOUR	Specific oxygen uptake rate
TAN	Total ammonia nitrogen
C_t:N	Total carbon to nitrogen ratio
TS	Total solids
UAN	Un-ionized ammonia
UAlberta	University of Alberta

CHAPTER 1: BACKGROUND INFORMATION AND RESEARCH OBJECTIVES

1.1 Organic waste

Municipal solid waste can be classified into two categories: organic (also known as biodegradable waste) and inorganic (also known as non-biodegradable waste). The organic fraction of municipal solid waste (OFMSW) includes food and kitchen waste, paper, and green waste. Inorganic waste is composed of materials such as glass, plastics, metals, etc. The two sources of OFMSW generation are 1) the residential sector and 2) institutional, commercial, and industrial (ICI) sectors.

Residential waste includes waste generated from single and multi-family, high-rise and low-rise residences picked up by municipalities or self-hauled to depots, landfills and transport stations (Statistics Canada 2013). ICI waste is comprised of materials generated by manufacturing, industries, commercial operations (e.g. shopping centres, restaurants, offices, and others), and institutional facilities, (e.g. schools, hospitals, government facilities, seniors' homes, universities, and others) (Statistics Canada 2012). The results of a study in the Alberta Capital region showed that organic and paper waste are the two major compositions in both residential and ICI sectors. The residential sector includes 35% and 25% of organic and paper waste respectively, while these amounts change to 25% and 33% in ICI sectors (EBA 2013). Therefore, to increase the diversion rate, waste management plans need to target these two streams, which have a high diversion potential. Diverting materials from residential sectors is typically relatively easy because of municipal controls on collection systems. However, in the ICI sector, it is more challenging to come up with an individual plan to meet diversion goals since each private sector is responsible for their generated waste and collection systems are under the mandate of private companies. Based on the latest data derived from Statistics Canada, the diversion rate for the residential sector in Alberta is 34%. This amount is about three times lower in the non-residential sector, including the ICI and Construction and

Demolition (C&D) sectors. In the following paragraphs, the ICI waste situation was investigated more in-depth in the Edmonton capital region (ECR).

1.2 ICI waste in Edmonton Capital Region

The Edmonton capital region (ECR), which includes the City of Edmonton and 34 other municipalities in the surrounding areas, has an area of 11,993 km^2. The total population of the ECR was estimated at 1.18 million, which is 31.8% of the total Alberta population, in 2010. Based on the latest Labour Force Survey, 640,000 of this population were employed in 2010 (Government of Alberta 2012). Edmonton, which is located on the North Saskatchewan River, is the most northerly major city in North America. Edmonton is the capital city of Alberta, with a population of 812,201 as of 2011. The area of the city of Edmonton itself is about 684 km^2 (Statistics Canada 2012). Edmonton has a widely varying seasonal weather and climate, with warm summers and cold winters. The highest and lowest temperatures recorded were 38.3 °C and -49.4 °C, respectively. The average daily temperature ranges from -11.7°C in January to 17.5°C in July (Environment Canada 2012). The City of Edmonton counts on the Waste Management Utility (WMU) to fulfill the needs of its citizens, to preserve natural resources, and to protect the environment and financial capabilities of the City. In 2010, 401,000 tonnes of residential waste, 486,000 tonnes of ICI waste and 328,000 tonnes of C&D were generated in the ECR (Office of the City Auditor 2011). This means that the overall waste generated is 1,215,000 tonnes, including 33% residential waste, 40% ICI waste and 27% C&D waste.

There have not been any studies done on ICI waste diversion rates in the ECR. The only diversion rate reported was related to total MSW, including residential, ICI and C&D, which was 22% as of 2006 in the City of Edmonton (Office of the City Auditor 2011). Due to the lack of sufficient study on the ICI waste composition in the ECR, it was necessary to evaluate the ICI waste audits from various cities in North America in order to come up with a first estimate of ICI characteristics in the ECR.

The first city considered was Calgary, Alberta, because it is located in the same province as Edmonton and is of a similar size, which likely makes it the most similar city

to Edmonton. According to Calgary's waste audit, done in 2010, the waste sent to landfill was about 314,500 tonnes, including 50% ICI waste, 30% residential waste and 20% C&D waste. CH2M Hill, who conducted this waste audit study, used an ICI waste generation modeling exercise based on employment statistics for the city. 834,000 employees working in 18 business sectors produce Calgary's ICI waste (Kelleher Environmental 2011). The main target of this audit was to gather information that would be useful in achieving an 80% diversion of ICI waste from landfill by 2020. To achieve this goal, various collection systems and servicing frequencies are needed because of the different types, sizes and shapes of ICI waste. Thus, in ICI diversion programs, the specific waste generators (e.g. offices, restaurants, hospitals), the material type (e.g. food, paper & cardboard, plastic) and material categories (e.g. organics, recyclables, electronics) should be targeted.

In the report, the top four ICI waste generators, producing 50% of the ICI waste in Calgary, were identified (Kelleher Environmental 2011). The four largest generators (i.e. sectors) in the city recommended as a priority for diversion were accommodations and food services, retail trade, health care and social assistance, and manufacturing. The material types in the ICI waste stream were also modeled. Paper (36%) and food waste (26%) were identified as the two largest material streams in Calgary's ICI waste.

In order to reach more general conclusions about ICI waste composition, other ICI waste studies in Canada and the United States were also investigated (GENIVAR 2007, Koole 2011, Rudder et al. 2007, Edwards 2008, Technology Resource Inc. 2008, Kvick 2010) Similar to Calgary's ICI waste composition, food and paper wastes, comprising an average of 24% and 27%, respectively, are consistently the two largest components of ICI waste. It was concluded that diversion programs need to target these two streams, which have a high diversion potential through recycling and composting activities, respectively.

1.3 Higher education institutional waste

Among the ICI sectors, Higher Education Institutions (HEIs) commonly have a high commitment to sustainability. To evaluate the existing generation rate and diversion rate

at post-secondary institutions, waste audit studies from eight universities in Canada have been taken into consideration. The results of each of these studies are summarized in Table 1.1.

In order to calculate the total waste and biowaste generation rates, the overall waste generation amounts and population data were needed. The audit report of each university was reviewed to obtain this information. When a report had missing data, the universities were personally contacted. Unfortunately, it was not possible to collect all of the information needed for the purposes of this project from all of the universities. Unavailable data is indicated by a hyphen in Table 1.1. From the available information, the minimum, maximum, average and median values of biowaste generation, overall diversion rate and biowaste diversion rate were calculated. Two sets of statistics are presented in Table 1.1. The first set includes all of the studied universities and the second set includes only those universities that had comparable data. The second set of statistics was recommended to calculate the design values of the selected biowaste treatment for large post-secondary institutional waste.

Table 1.1. Summary of overall waste generation in Canadian universities

Universities	Overall waste[1]	Population[3]	Total waste generation rate	Biowaste [6]	Biowaste generation rate	Overall diversion rate	Biowaste diversion rate	Reference
	(tonnes/year)		($kg \cdot cap^{-1} \cdot y^{-1}$)	%	($kg \cdot cap^{-1} \cdot y^{-1}$)	%	%	
UAlberta (2005)	3,600	34,179[4]	105.33	39	41.08	21.8	0	[7]
UAlberta (2011)	3,300	37,240[4]	88.61	42	37.22	32.4	3.2	[8]
University of British Columbia (UBC)	-	67,546	-	41	-	44	10	[9]
McMaster University	2,517	26,710[4]	94.23	43	40.52	44	6.4	[10]
University of Toronto (U of T)	5,588	60,000	93.13	36	33.53	68.19	19.4	[11]
Queen's University	2,838[2]	20,069[4]	141.41	69.5	98.28	43	-	[12]
Dalhousie University	1,151[2]	-	-	26.1	-	-	-	[13]
Brock University	1,691	18,594	90.94	37	33.65	78.9	26.49	[14]
University of Manitoba (U of M)	1,797	23,399[5]	76.8	21	16.13	21	0	[15]
Descriptive statistics for all of the studied universities								
Min	1,151	18,594	77	21	16	21	0	
Max	5,588	67,546	141.41	69.5	98.28	78.9	26.49	
Average	2,810	35,967	98.64	39.4	42.92	44.16	9.36	
Median	2,678	30,445	93.13	39	37.22	43.5	6.4	
Descriptive statistic for comparable institutions (U of A 2005, U of A 2011, McMaster university, U of T, Brock university)								
Min	1,691	18,594	88.61	36.00	33.53	21.80	0.00	
Max	5,588	60,000	105.33	43.00	41.08	78.90	26.49	
Average	3,339	35,344	94.45	39.40	37.20	49.06	11.10	
Median	3,300	34,179	93.13	39.00	37.22	44.00	6.40	

[1] For overall waste, most of the universities reported values based on the total waste generation. Queen's and Dalhousie reported based on the waste sent to landfill. Additionally, UBC's waste audit report lacked information regarding overall waste.
[2] This value is comprised of the waste sent to landfill.

[3] Population data for most universities was calculated based on Sustainability Tracking Assessment and Rating Systems (STARS) guidelines. In contrast, the university of Manitoba used the Full-Time Equivalent staff & students (FTE) method for population calculation. The method used to calculate population was not specified for UBC, University of Toronto and Brock University.

[4] Population calculated using the STARS guideline. The weighted campus users were calculated with the following equation:

$$Weighted\ campus\ users = 1.0 \times R + 0.75 \times F + 0.5 \times P$$

Where, R is the number of on-campus residents

F is the number of non-residential full-time students and staff

P is the number of non-residential part-time students and staff

[5] Population calculated using the FTE method. FTE was determined by the formula: $FTE = Full - time + (part - time/3.5)$ (Office of Institutional Analysis, 2012)

[6] For biowaste value, each university considered specific types of materials as biowaste. In the U of A waste audit, biowaste is comprised of food waste, paper towel/tissues, and animal bedding. UBC reported food scraps, food-soiled paper and campus yard trimmings as "compostable organics". The McMaster University report referred to "compostables", which are comprised of food waste, flowers, yard waste and animal waste. Paper towel is considered in the paper fibres stream. The only materials included in the organics stream in the U of T, Queen's and Brock University's waste audits was food waste. Dalhousie university reported food waste and paper towel in the organics stream.

[7] (KC Environmental Group Ltd. 2006)

[8] (Yan, McCartney 2011)

[9] (Giratalla, Rowlands 2010)

[10] (Hall 2011)

[11] (Envirovision Inc. 2011)

[12] (Queen's University 2011)

[13] (Davidson 2011)

[14] (UNWIN & Assoc. 2010)

[15](McCartney, Friesen 2009)

1.4 Organic waste treatment technologies

Interest in organic waste treatment has increased a lot in recent years due to its high generation rate. By using organic treatment technologies such as anaerobic digestion (AD) and composting, the organic material can be diverted away from landfill, thereby reducing greenhouse gas emissions while producing valuable by-products. In addition, increasing the diversion rate of this stream has a useful role in increasing the total diversion rate of municipal solid waste. The two main biotransformation technologies, AD and composting, are described in the following sections.

1.4.1 Anaerobic digestion

Anaerobic digestion (AD) is the biological decomposition of organic waste streams in the absence of oxygen. The microorganisms involved naturally thrive in wet, nutrient-rich and oxygen-free environments. Optimal anaerobic digestion takes place under stable and balanced conditions. The best way to create optimal conditions is to set a stable temperature, maintain near-neutral pH levels, provide sufficient nutrients, and eliminate toxins in the digester.

Digestate and biogas are the final products of the AD process (Hilkiah Igoni et al. 2008). Digestate is the solid residues generated from the biodegradation of organic waste during the anaerobic digestion process. It is a valuable soil conditioner; however, this high moisture content by-product is not fully stabilized, and when applied to land as a fertilizer, there is an increased risk of odour complaints, potential for phyto-toxic responses, and some difficulties in handling the materials (Teglia, Tremier & Martel 2011) . Therefore, management of a high volume of digestate is one of the challenges that AD plants currently face.

Biogas typically contains 60% to 70% methane (by volume), 30% to 40% carbon dioxide and minor quantities of nitrogen, hydrogen, ammonia and hydrogen sulfide (usually less than 1% of the total gas volume) (Ahring et al. 2003) Fluctuations in pH and alkalinity affect the process activity and cause variability in the produced biogas

composition. Both pH and alkalinity are affected by the influent substrate composition (Gerhard B. Ryhiner, Elmar Heinzle, and Irving J. Dunn 1993). This means that the composition of the produced biogas is influenced by the substrate characteristics in the influent of a digester (APHA 1999). The typical biogas production in the anaerobic digestion systems is approximately 0.70 to 1.25 m^3/kg VS (Tchobanoglous 1979, Weiland 2010) . Biogas is widely used as a source of energy, heating and electricity, due to its moderate heating value. It can also be applied as a vehicle fuel after being treated and upgraded in a biofuel process. Upgrading includes the removal of impurities such as CO_2, H_2S, H_2, particulates, water vapour and siloxanes by scrubbers or adsorbants, such as activated carbon. Although biogas can be used as a source of energy, releasing it to the atmosphere has environmental impacts in the form of greenhouse gas emissions (CH_4 and CO_2).

Consequently, AD has remarkable advantages such as volume reduction, biogas production and the creation of a useful biosolids product that can be used as a soil fertilizer in contrast to the other technologies. This technology could be environmentally beneficial if the produced biogas is captured rather than released into the atmosphere.

1.4.1.1 Anaerobic digestion technologies

There are different technologies for anaerobic digestion. The digestion system can be:

- Dry, semi-dry or wet (containing typically 20-40%, 10-20%, <10% dry matter, respectively);
- Thermophilic (55-65°C) or mesophilic (25-40°C);
- Continuous, semi-continuous or batch;
- One stage or two stage processes (Tchobanoglous, Burton & Stensel 2003)

In the dry digestion systems (high solids), total solids content is between 20 and 40%. Such systems do not need any specific pre-treatment procedures, aside from adjusting the solids content to the desired range and removing pieces larger than 5cm. They have good flexibility in the acceptance of non-biodegradable materials such as

plastics, metals, glass, and rocks. Although these materials will not play any role in biogas production, they do not have any impact on the conversion of biomass components.

In wet digestion systems (low solids), in order to create pumpable slurry, the digester contents are kept at a total solids content below 20%. To achieve an appropriate range for solids content, co-digestion of MSW with more dilute wastes such as manure or sewage sludge, and the addition of recycled process water is recommended (Bolzonella et al. 2003).

In high solids systems (dry anaerobic digestion), more biogas is produced compared to low solids systems. Due to mass transfer reduction, high dry matter content also reduces transport costs. A smaller reactor size is required in dry systems in comparison to wet systems, leading to a lower process energy demand for heating, which is the other advantage of this system (Schafer, Lehto & Teye 2006) . However, high solids systems also have disadvantages compared to low solids systems, such as longer retention time, and greater energy requirements for handling, mixing and pumping materials with high solids contents. Pumping facilities in dry systems are usually more expensive than in wet systems. However, materials handling expenses may be offset by the lower costs of pre-treatment (Schwarzenegger, Adams 2008) .

1.4.2 Composting

Composting is an important alternative technology for managing organic waste. Composting is the degradation of organic matter by microorganisms, which occurs under aerobic conditions and results in the production of stable solid compounds as a final product. This stable material contains relatively large amounts of humic compounds, and has a high degree of sanitization. It can be used as a soil conditioner and is beneficial for soil stabilization.

During composting, organic matter is converted by the aerobic microorganisms into compost, CO_2 (the main gaseous emission from the composting process), other gases

such as NH_3, water and heat. The following relationship represents the composting process:

$$organic\ matter + O_2 \rightarrow compost + CO_2 + NH_3 + H_2O + heat$$

Composting has gained tremendous popularity due to the several advantages it offers. In terms of environmental and ecological advantages, during composting organics derived from municipal solid waste, food industries, livestock, farming, and even sludge from wastewater treatment plants are converted to a stable humus-like material known as compost, which is a useful product for agriculture. In terms of hygienic issues, the high temperatures generated during the process destroy pathogenic organisms and weed seeds. In terms of energy usage, the process uses energy released from the decomposition of organic matter due to the destruction of biochemical bonds. Although the energy generated during composting is not captured, energy can be saved when substituting the compost product for artificial soil conditioners and fertilizers.

1.4.2.1 Composting technologies

There are two different systems used in composting processes: open systems and enclosed systems. Open systems are implemented outdoors or in partially enclosed buildings. Enclosed systems are carried out in restricted/closed environments in order to have better control over the gases discharged during composting. Enclosed systems have several advantages, including less sensitivity to meteorological conditions, less spreading of biomass into adjacent ecosystems and reduction of environmental impacts due to control of gaseous emissions. However, open systems also work well and generally have lower costs associated with them.

Composting systems are divided into two categories relating to the type of facility: windrow composting and reactor composting. Windrows are outdoor systems, and the feedstock material is treated in piles with various dimensions. Windrows are divided into various categories based on the method of providing oxygen to the feedstock (for

example, turned windrows, passively aerated static piles, and actively aerated static piles).

In reactor composting systems, all of the biological activities occur in a completely enclosed, rigid structure or vessel. Most of these systems are equipped with air treatment facilities in order to control the emission of particulate and gaseous pollutants into the atmosphere (Chiumenti et al. 2005).

1.4.2.2 Microbial community

Composting is a microbial process derived from a high diversity of microorganisms. The aerobic microorganisms participating in the composting include fungi and bacteria and actinomycetes. Other groups, such as algae and protozoa, are of minor significance. The microbial community participating in composting is naturally found in compost feedstock and is affected by the input substrate (Klammer et al. 2008). Since the input substrate of composting is usually heterogeneous, the initial microbial population also has high diversity. However, inoculum or additive can also be added to modify the microbial community and improve the process efficiency.

During the composting, temperature plays an important role in determining the microbial population. In the beginning of composting, when the temperature is still close to the ambient temperature, mesophilic microorganisms are dominant. The microbes that govern this stage are bacteria and fungi, which are responsible for the degradation of readily available organics such as sugars, proteins and fats. However, fungi are usually outcompeted by bacteria for easily degradable substrate. This can be explained by higher specific growth rates of bacteria compared with those of fungi by one order of magnitude (Insam, Riddech & Klammer 2013) .

At the latter stage, during the thermophilic phase, the activities of mesophilic microbes are reduced due to inhibitions in their metabolism and the majority of them die or become inactive. This stage is characterized by an increase in the number of thermophilic organisms, mostly bacteria, which are responsible for breaking down the less biodegradable organics such as cellulose, hemicellulose, and the remaining easily degradable substrate. Although some thermophilic fungi and actinomycetes have been

identified at the thermophilic stage, they usually do not thrive at high temperatures (above 55 °C) and low oxygen concentrations. It should be noted that anoxic conditions may even occur in force-aerated composting systems (Epstein 1996).

As the organic matter is degraded and nutrient sources become limited, the microbial activities are reduced. As a result, the heat generation declines and the process enters the curing phase. At this phase, mesophilic organisms, mostly comprising of fungi, actinomycetes and a reduced number of bacteria, start to recolonize. They engage in breaking down hardly degradable compounds and long polymers such as lignin while the first mesophilic phase is characterized by an increased number of organisms that target easily degradable substrate. Environmental factors (lower pH, moisture content and temperature, higher concentration of oxygen and less substrate availability) governing this phase are a favourable condition for the presence and activity of fungi and actinomycetes (Christensen 2011).

1.4.2.3 Physicochemical parameters

As microorganisms play an important role in the composting process, providing appropriate conditions for their activity is essential. Therefore, optimizing the following physical and chemical parameters can improve the composting process performance.

- Free air space (FAS);
- Moisture content (MC);
- Oxygen and aeration;
- Temperature;
- Elemental composition: Carbon, Nitrogen and Carbon to nitrogen ratio (C:N);
- Other nutrients (P, S, K, Mg, Ca, Na, Fe, Mn, Zn and Cu);
- pH

The composting matrix includes solid particles and pore space, which is filled with water and air. The portion of the pore space that is filled only with the air is called FAS. Maintaining the optimum FAS during composting is necessary to ensure air movement

throughout the mixture. When the MC is too high or the feedstock is too compacted, oxygen transfer becomes restricted and the system changes from aerobic to anaerobic conditions. TMECC (03-01) suggests that the FAS of the feedstock should be greater than 60% and 35% at the initial and curing phases of composting, respectively. Amendments or bulking agent such as woodchips or sawdust can increase the FAS because of their structure and absorbency.

MC is an essential factor to support microbial activity. The suitable moisture content for the composting process differs among various types of wastes. For example, the MC should be in the range of 75-85% for the composting of fibrous and bulky material such as yard wastes with higher water holding capacity (Haug 1993). While this range changes to 40-60% for the composting of municipal solid waste (Tchobanoglous, Theisen & Vigil 1993) . When the MC is lower than its suitable range, the microbial activity is drastically reduced and when it is higher than its suitable range, the void space is filled with water and air movement through the materials is prevented.

Composting is an aerobic process, therefore providing enough oxygen to ensure the optimal performance of aerobic microorganisms in necessary. There are three different purposes for intruding air into the composting processes. First, to ensure the optimal performance of aerobic microorganisms, second, to dry and remove MC from wet feedstock, and third, to remove heat generated during the degradation of the organic matter (Haug 1993). Therefore, aeration control is one of the key points in composting because any of the three mentioned purposes (microbial activity, high MC and temperate) can inhibit the process by affecting the microbial activity.

Temperature is another important process control parameter during composting. On the one hand, temperature is an indicator of the microbial activity and it varies as a direct consequence of heat generation. On the other hand, it is a determinant of the microbial population (Gea et al. 2007). While a high temperature is required to ensure sanitization (pathogen and weed seed destruction), extremely high temperatures (i.e., over 70 °C) can also limit the microbial activity (Wichuk, McCartney 2010) . Moreover, in composting with high temperatures for long periods of time, nitrogen loss increases due to high

ammonia emissions (Eklind et al. 2007). The optimum temperature to maximize the biodegradation rate lies in the range of 50 to 60 °C (Epstein 1996).

Although microorganisms require more than 30 nutrients for their cell growth, 98% of their dry weight is comprised of eight elements, six non-metals (carbon, nitrogen, oxygen, hydrogen, sulfur, and phosphorus) and two metals (potassium and magnesium) (Reddy et al. 2007)

Carbon and nitrogen are the two principal nutrients required in large amounts in all living systems. Microorganisms consume carbon as an energy source and for growth and nitrogen for biosynthesis. Therefore the balance between C and N (C:N ratio) is an important parameter, which should be taken into consideration before any biological process. Determination of the optimum C:N ratio is of great interest in the composting process. Suitable balance between carbon and nitrogen in the feedstock improves the efficiency of microbial metabolism and decomposition of the organic material, while an unsuitable range may cause the loss of excess nitrogen by ammonia volatilization which causes odour problems or leads to a high VFA accumulation. Microorganisms require 25 to 30 parts C for every unit of N (Epstein 1996). Many articles suggested the range of 20-30 for C:N ratio as an optimum range for microbial growth (Álvarez, Otero & Lema 2010, Brown, Li 2013, Li, Park & Zhu 2011) .

Phosphorus is another primary nutrient required by microorganisms to synthesise nucleic acids and build-up phospholipids as well as cell wall constituents of gram positive bacteria (teichoic acids). Although not as critical as the C:N ratio, C:P ratio should also be taken into consideration in order to have efficient biological degradation during composting (Brown, Bouwkamp & Gouin 1998) . Since phosphorus, nitrogen, and potassium are required nutrients for plant growth, the concentrations of them are also important in determining the quality of the final compost (Stoffella, Kahn 2001) .

Sulfur is an essential element because of its structural role in building amino acids (cysteine and methionine), and developing enzymes and vitamins (biotin, thiamin and lipoic acid) (Reddy et al. 2007). Protein materials are the major sources of sulfur in composting. If sufficient air is provided to the composting material, sulfide is oxidized to

the sulfate. While, in the case of poor aeration and under anaerobic digestion, organic sulfide and hydrogen sulfide are volatilized into the atmosphere and cause odour problems in composting facilities (Stoffella, Kahn 2001) .

Potassium and magnesium are the two metal nutrients required for cell growth. Potassium is essential in carbohydrate metabolism and for the transport of nutrients by providing cation balancing and increasing the permeability of cell walls while magnesium plays a key role in ribosome and nucleic acid stabilization.

Calcium is a constituent of membranes and cell walls and involved in the activation of many enzymes that results in the enhancement of microbial activity (Reddy et al. 2007, Kayhanian, Rich 1995) .

Micronutrients include sodium, iron, manganese, cobalt, copper, zinc, nickel, selenium, chloride, and boron. They are required in small amounts (ppm) and are usually necessary for the optimal growth of microorganisms.

The pH, an indicator of hydrogen ions concentration, is a chemical property that affects microorganism growth by changing their enzymatic activity. Both high pH (high OH^- concentration) and low pH (high H^+ concentration) are very toxic to microorganisms. However, carbon dioxide and ammonia generation as a consequence of organic degradation during composting neutralizes the high or low pH of the initial feedstock (Haug 1993). At the initial stage of composting, pH usually decreases due to the activity of acid-forming bacteria. As composting progresses, pH increases while organic acid is consumed and ammonia released (Petric, Helić & Avdić 2012) . The final pH of the material is usually slightly alkaline, in the range of 7.5-8.5 (Stoffella, Kahn 2001) .

1.4.2.4 Composting inoculation

Composting is a well-known microbial process for the stabilization and humification of organic matter in which microorganisms play key roles. However, deficiencies in the indigenous microbial community can lead to a low composting efficiency and

consequently affect the compost quality (Xi et al. 2012). The benefits of direct microbial inoculation into composting substrates still remain uncertain. Barrena et al. (2006) reported that adding inoculum to compost accelerates the overall composting process. Inoculation with pure yeast strains could eliminate the initial composting lag phase and improve the overall efficiency (Nakasaki, Araya & Mimoto 2013) . Conversely, Golueke et al. (1954) indicated that the indigenous microorganisms that exist in the compost are sufficient and the inoculation of compost with pure microbial strains does not have a positive effect on the overall process performance. Wei at al. (2007) observed that mixed inoculum containing varied species of microorganisms with lingo-cellulotyc microbial communities enhanced the composting maturation phase. The improvement in the maturity phase by inoculation with pure microorganisms was also documented by Huang et al. (2009). Enhancing the stability phase by adding external microbial cultures was also reported in related literature (Tiquia, Tam & Hodgkiss 1997, Bolta et al. 2003) .

Co-composting is another method of inoculation that has drawn much attention, because it enhances the performance of the composting process and helps to manage a variety of organic waste streams. It can be more economically beneficial compared to direct microbial inoculation because, in this method, instead of purchasing or preparing the specific type of microbe, the waste is co-composted with another type of waste that already contains various microbial communities. Therefore, not only does the composting process benefit from the inoculation but also the inoculant (waste) is undertaking further treatment. Co-composting of a 3:1 (v/v) mixture of municipal solid waste and sewage sludge resulted in a significant improvement of organic matter degradation and final nitrogen content in the compost (Lu, Wu & Guo 2009) .

Digestate is another type of waste that can be used as an inoculant in the co-composting process. Several studies (Abdullahi et al. 2008, Pognani et al. 2012, Bustamante et al. 2013, Walker, Charles & Cord-Ruwisch 2009, Himanen, Hänninen 2011, Rehl, Müller 2011) have evaluated the composting of anaerobic digestate as a sole feedstock. However, to the author's knowledge, the co-composting of digestate obtained from AD plants has yet to be fully investigated. De Baere (2008) monitored a full scale MBT (mechanical biological treatment) plant for over a year in Germany. The plant was

an anaerobic reactor (with a volume of 2,260 m^3 and a retention time of 21 days) with heated and non-heated tunnels for the composting process. It was found that mixing the anaerobic digestate with non-digested organics reduced the composting time from 9 weeks to 5 weeks (45% reduction in material retention time). This was accomplished with a mixture of digestate to organics of 2:1(w/w). Co-composting of thermophilic digestate and organic municipal solid waste (MSW) with the only mixture ratio of 1:2 (v/v) was investigated by Pera et al. (1991). In this study, the MSW was applied as an amendment to the digestate composting process and resulted in a greater sanitation degree of the organic biomass and a better final product. Overall, the literature review revealed that the co-composting of anaerobic digestate with organic waste can bring some advantages to the composting process (Monnet 2003, De Baere 2008, Szucs, Simon & Fuleky 2012) .

The inoculating time is another influential parameter that has been a controversial subject for a long time, and due to the lack of a clear agreement on the subject it still requires further investigation. Xi et al. (2005) studied the microbial kinetics during composting inoculation and demonstrated that microbial concentration is a main limiting factor in the first stage (degradation phase) while the substrate concentration is the key limiting factor in the second stage (maturity phase). According to this study, inoculation during the first stage seems to be more effective in order to speed up the composting process. However, some authors (Huang et al. 2009, Zeng et al. 2010) suggested that inoculation during the second phase (curing phase) can more effectively accelerate the overall composting process. This controversy is not surprising because of the complexity of composting microbial reactions and the lack of our understanding of all the interactions, mechanisms and processes that lead to the end results. Therefore, these observations suggest that in order to benefit from composting inoculation the quantity and time of inoculation should be carefully investigated. Composting inoculation with digestate can enhance the amount and diversity of microbial populations and possibly improve the overall performance if the quantity and time of inoculation can be adjusted appropriately. In addition to existing mutual microorganisms and positive interaction effects, applying digestate as an additive into the composting facility provides reliable nutrient sources such as nitrogen and phosphorus as well as micronutrients such as

magnesium and iron for the compost and may help to speed up the overall composting process.

In addition to the biological effects, digestate can also improve the physical properties of the composting process (e.g. providing the moisture content for low moisture content compost feedstock) (Monnet 2003). However, if the digestate is used as a sole feedstock in composting, it should be dewatered before the process and the excess wastewater needs to be treated. Co-composting of digestate with non-degraded organics may negate the need to dewater the digestate. The remaining energy in undigested organics helps to dry and stabilize the whole mixture of digested and non-degraded organics; therefore, excess wastewater may not be produced (De Baere 2008). In spite of all the possible advantages that digestate can have on the composting process, the literature review revealed that the lack of enough information about the co-composting of digested and non-digested organics is noticeable and the need for thorough investigations on the knowledge gap in this area is critical.

1.5 Problem statement and research objectives

Organic waste has become one of the largest waste streams around the world. The interest in organic waste treatment has increased in recent years. Among the treatment technologies, anaerobic digestion (AD) has gained a significant role in municipal solid waste management due to its energy recovery benefits (Liu et al. 2012, De Baere 2008) . In the City of Edmonton (CoE), 32% of residential waste is comprised of organic waste (23% of food waste and 9% of other organics) (Waste Management Branch 2010). The University of Alberta (UAlberta) and Waste Management Services (WMS), has a joint partnership that involves implementing a high solids anaerobic digestion facility (HSADF) at the Edmonton Waste Management Centre (EWMC). This will be the first facility of this type in Alberta. By operating the HSAD facility, 40,000 tonnes of organic waste will be diverted annually from landfill and composting facilities. This leads to a reduction in greenhouse gas emission by displacing the energy sources required to aerate the compost facility and also avoiding methane emission through landfills. The long-term

plan is to have source-separated organics (SSO) from the institutional, commercial, and industrial (ICI) sector as the primary feedstock. UAlberta, as a higher education institution, is expected to contribute 1,500 wet tonnes of SSO. Although UAlberta's contribution is relatively small, characterization of its organic waste stream is needed to further assist in designing the facility.

Therefore, the first objective of this research was to propose a sampling methodology to characterize UAlberta's organic waste stream that would be destined to the HSADF at the EWMC. The characterization included estimating the physical, chemical, and biological properties of organic waste collected from UAlberta's whole campus.

One of the challenges that AD plants currently face is the management of a high volume of digestate, generated from the biodegradation of organic waste during the anaerobic digestion process. Composting is typically used to improve the digestate quality. Post treatment of the digestate in a composting process can assure the maturity and stability of this by-product once applied to the land. The digestate from the AD process can also be mixed with fresh and/or composted organic waste and then fed to the composting and/or curing process. The City of Edmonton is integrating the new HSAD technology into its existing composting facility. Four general options are available for integrating the anaerobic digestion process into the City's organics processing waste stream (Figure 1.1):

1) Compost and cure separately;
2) Co-compost (mix with fresh OFMSW) and cure;
3) Aerate and cure separately;
4) Aerate separately and co-cure (mix with 21-day composted OFMSW).

However, implementing any of the aforementioned options needs a comprehensive study on process performance and efficiency and on their economic aspects.

Thus, in addition to the aforementioned purpose, investigation of various options of digestate post-treatment is another intent of this research. Based on this purpose, the key objectives include:

1) To investigate the effects of added digestate at the beginning of the composting

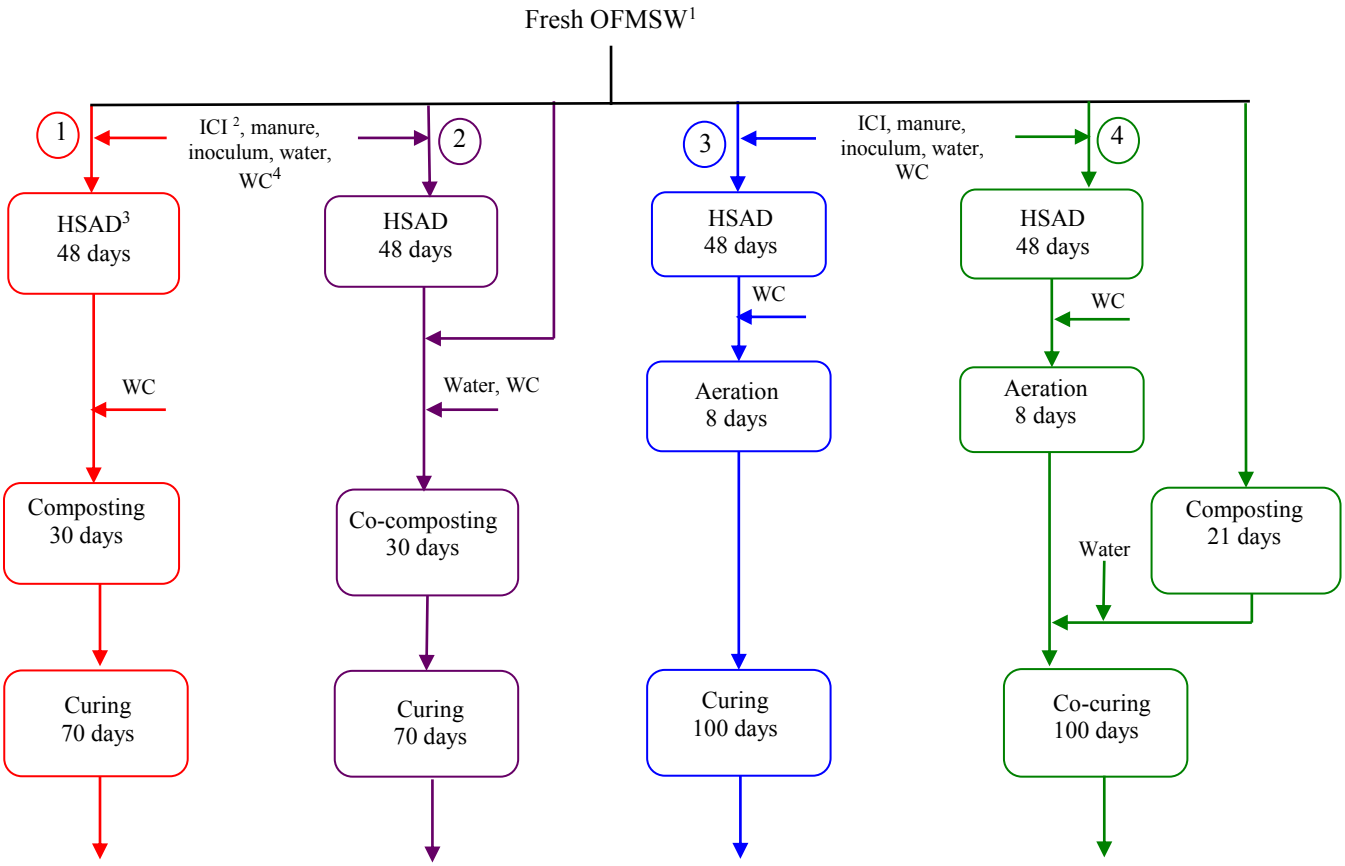
process in terms of

1.1) physicochemical parameters

1.2) microbial population dynamics

2) To investigate the effects of added digestate at the curing phase of the composting process.

In the experimental design, the focus was on the material streams available to the City of Edmonton, including feedstocks and compost products. Also, the mixing ratios (of digestate to fresh or composted OFMSW) are selected based on the available full-scale quantities in the CoE. This will add to our fundamental understanding of digestate composting and will provide the City of Edmonton with important design and operation information for digestate treatment. By improving the rate of composting, the organics processing system at the CoE's Waste Management Services will benefit from the energy production in the AD process, as well as dramatically lowering energy requirements for aeration during the composting process and consequently reducing their operating costs. In addition, the reduction in material retention time would significantly decrease the necessary capacity of the composting process and allow a higher throughput for an existing composting system.



[1] Organic fraction of municipal solid waste.
[2] ICI: institutional, commercial and industrial organic waste, [3] high solids anaerobic digestion, [4] woodchips.

Figure 1.1. Material flow showing four possible integration scenarios for the anaerobic digestion facility at CoE.

1.6 Thesis outline

This thesis consists of six chapters focusing on organic waste characterization and different options of digestate treatment when integrating anaerobic digestion into a composting facility. The general overview of the organic fraction of municipal solid waste as well as the generation sources and related treatment technologies (anaerobic digestion and composting) are discussed in Chapter 1.

Chapter 2 provides an overview of the best practices used to estimate the waste quality at large institutions. A sampling methodology was also proposed to allow for the

testing of key waste quality parameters. The proposed methodology can be aligned with typical waste audits (quantification studies) at any higher education institutions (HEI's). Finally, the physical, chemical and biological characteristics of the organics generated at the University of Alberta are estimated according to the proposed methodology.

Four different options of digestate treatment available at the CoE (Figure 1.1) are investigated in chapters 3, 4, and 5. Options 1 and 2, with the focus of adding the digestate at the beginning of the composting process, are studied in Chapter 3 and 4. In Chapter 3, the changes of physicochemical parameters and possible benefits that organic waste and digestate can have on each other during co-composting are discussed. In Chapter 4, the effects of biological characteristics and microbial population on stabilization rates are investigated.

Options 3 and 4 are studied in Chapter 5. In this chapter, the effects of adding polished digestate at the curing phase of composting are evaluated and the findings are compared to the results achieved in options 1 and 2. Finally, the most suitable option is suggested considering the material characteristics and the operation process at the CoE.

In Chapter 6, the overall conclusions of the performed research as well as recommendations for future works are presented.

Some of the supplementary tables and figures to support the obtained results are presented in the Appendix sections at the end of this thesis. Materials related to Chapter 2, 3, 4, and 5 are presented in Appendix B, C, D, and E, respectively.

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Zeng, G., Yu, M., Chen, Y., Huang, D., Zhang, J., Huang, H., Jiang, R., and Yu, Z. 2010. Effects of inoculation with Phanerochaete chrysosporium at various time points on enzyme activities during agricultural waste composting. Bioresource Technology, **101**(1): 222-227.

CHAPTER 2: ORGANIC WASTE CHARACTERIZATION AT LARGE POST-SECONDARY INSTITUTIONS[1]

2.1 Introduction

2.1.1 Background

Biotransformation technologies, or organics processing facilities, are widely integrated into solid waste management systems across the world. These technologies focus on diverting the organic fraction of municipal solid waste (OFMSW) from landfill sites where some type of resource is recovered. Some examples of such technologies are bioreactor landfill, anaerobic digestion, and composting. Diverting the OFMSW has many environmental, social, and economical benefits, such as reducing greenhouse gas emissions, reducing the need for landfill sites, and producing valuable by-products (e.g. soil amendment and biogas) (Ng, Yusoff 2015, Hilkiah Igoni et al. 2008).

The organic fraction of municipal solid waste, also known as organics or bio-waste, commonly consists of food and kitchen waste (scraps and cuttings), soiled paper-based products, and leaf and yard waste. Municipalities have slowly shifted into organics diversion to achieve zero waste management. But, the efforts of organics diversion are still low. For example in European countries, recycling rates have increased from 28% in 2004 to 37% in 2012; however, the organic waste recycling has seen little improvement (EEA 2013, EEA 2009, EEA 2015). In Canada, the amount of materials diverted, either for recycling or composting, increased by about 21% between 2002 and 2010. But, diversion rate of organic materials rose only 7%, from 20% in 2002 to 27% in 2010 (Statistics Canada 2010, Statistics Canada 2013b, Statistics Canada 2007). In the United States the materials recovery rate for recycling was increased from 29% in 2000 to 35%

[1] A version of this chapter has been submitted as: Arab, G. and McCartney, D. "Organic Waste Characterization at Large Post-Secondary Institutions" in *Waste and Biomass Vaporization*.

in 2011. While the total recycling rate increased 6%, the organic recycling rate increased only 1%, from 7% in 2000 to 8% in 2011 (EPA 2013).

Also, most municipalities have primarily focused on waste diversion within the residential sector and pay less attention to non-residential sectors, such as the industrial, commercial, and institutional (ICI) sector (Waste Management Branch 2010). In Alberta, Canada, about 40% of the municipal solid waste is collected from the ICI sector and within the ICI stream 30% is estimated to be the organic fraction (Waste Management Branch 2010, Statistics Canada 2013a). While there is much potential for diversion of the organic fraction of ICI waste, two factors limit this in practice. First, because ICI waste collection is done by the private sector or waste generator, and not by municipal collection systems, economic factors, in addition to technical and environmental factors, are of particular importance. Thus, the diversion rate for this stream is generally lower than for residential municipal waste. Secondly, because of the variability of ICI waste composition, it is a challenge to come up with an organic waste treatment strategy for ICI as a whole sector. Thus, it is likely more useful to come up with ICI diversion strategies for specific regions, business sectors, or even specific companies or institutions, based on economic, technical and environmental factors (Waste Management Branch 2010). In order to reach more general conclusions about ICI waste composition, some ICI waste studies in Canada and United States were investigated. The results showed that food and paper wastes, comprising an average of 24% and 27%, respectively, are consistently the two largest components of ICI waste in municipalities (Table 2.1). Thus, diversion programs need to target these two streams, which have a high diversion potential through recycling and composting activities, respectively (GENIVAR 2007, Koole 2011, Edwards 2008, Technology Resource Inc. 2008, Kvick 2010).

Among the ICI sectors, Higher Education Institutions (HEIs) commonly have a high commitment to sustainability. HEIs are typically at the forefront of the sustainability movement, including the field of waste management. Not only there is a broad range of in-house expertise available, but also HEIs, as centres of learning and research, are well positioned to influence the values and behavior of students and staff, which over time will carry over to broader society.

For any institution, to develop or to further a waste management program one typically starts by characterizing the quantity and type of waste material. The quantity is related to the generation rate (amount of waste generated by waste category), while type is related to material properties or downstream processing technologies, e.g. glass or compostable organics. Many large institutions are implementing or investigating on-site biotransformation processes such as composting or anaerobic digestion, so it is also important to develop an understanding of the key waste quality parameters used in design, e.g. bulk density, moisture content, carbon to nitrogen ratio, and biological methane potential. The objective of this study was to propose a sampling methodology that can be aligned with typical waste audit (characterization studies) at any HEI to allow testing of key waste quality parameters. It also provides an overview of the best practices used to estimate waste quality at large institutions.

Table 2.1. Summary of Overall ICI Waste Composition Information From Various Studies.

City	Waste composition (%)								
	Food/ Organics	Paper	Plastic	Metal	Glass	Others	C&D (from ICI activities)	Wood	References
Seattle	31.3	24.7	4.7	-	-	3.1	-	-	
Los Angeles	41.7	32.1	11.7	3.9	2.0	1.2	11.3	-	
Vermont	36.6	20.2	4.9	1.6	1.6	35.1	-	-	
Wisconsin	21	26	15	-	-	8	16	-	(GENIVAR 2007)
Minnesota	30	35	12	-	-	23	-	-	
Pennsylvania	11.8	29.7	9.9	3.3	-		13.3	-	
San Francisco	29.8	16.1	5	-	2.7	6.1	3.8	-	
Calgary	26	36	9	8	3	11	-	7	(Koole 2011)
Ottawa	16	32	10	10	5	27	-	-	(GENIVAR 2007)
Regina	13	46	10	11	4	8	-	8	(GENIVAR 2007)
Saskatoon	21	21	12	8	1	14	-	23	(Rudder et al. 2007)
Burin Peninsula	15	42	13	6	4	11	-	9	(Edwards 2008)
Metro Vancouver	41	27	15	4	2	7	4	-	(Technology Resource Inc. 2008)
Victoria	31.7	21.2	14.7	3.1	1.8	18.2	3.2	6.1	(Kvick 2010)
Average	24.4	27.3	9.8	5.5	2.5	12.4	8.0	9.9	

2.1.2 Study location

This paper presents a case study at University of Alberta (UAlberta), a public research university located in Edmonton, Alberta, Canada, established in 1908. It currently has over 53,000 students and employees (University of Alberta 2016).

The UAlberta has a long-standing commitment to sustainability and has implemented numerous diversion strategies and plans since 2005 to improve its solid waste management (such as collecting additional recyclable and compostable materials, increasing awareness of sustainable activities, and providing education of waste diversion to staff members and students). The UAlberta has made significant changes towards diverting waste to landfill sites by recycling recyclable materials and composting organic materials and currently diverts a wide range of materials from paper to electronic waste. At the time this research was conducted, the University had set a waste reduction target of diverting 50% (by mass) of landfill waste by 2015. By 2015, they actually achieved 55% diversion. Their new Sustainability Plan (2016-2020) has set a goal of diverting 90% of their waste from landfill. To achieve a higher diversion rate, UAlberta committed to a joint partnership with the City of Edmonton for implementing a high solids anaerobic digestion facility (HSADF) at the Edmonton Waste Management Centre. The HSADF is expected to process 40,000 wet tonnes of the organic fraction of municipal solid waste. The UAlberta, as an institutional sector, is expected to contribute about 1,500 wet tonnes per year of source separated organics (SSO).

2.2 Materials and Methods

2.2.1 Sample collection and processing

Given the significant spatial and temporal waste generation variability on a university campus, the development of a representative sampling plan involves trade-offs among accuracy, cost, and time. In this study, two different sampling approaches were performed. The first batch of samples was characterized for their physical and chemical characteristics and the second batch was analysed for its biological characteristics. Waste characterization (quantity) sampling methodology was used to collect samples for quality data. Detailed steps in each sampling plan are described in the following paragraphs.

2.2.1.1 Physical and chemical test samples

In this study, the representative samples to conduct physical and chemical analyses were collected in conjunction with the waste audit conducted at UAlberta in 2012. Samples were collected from seven food services buildings listed in Table 2.2 and were observed to contain food waste, biodegradable fibres, and washroom paper towel.

Table 2.2. Summary of Sampling Program

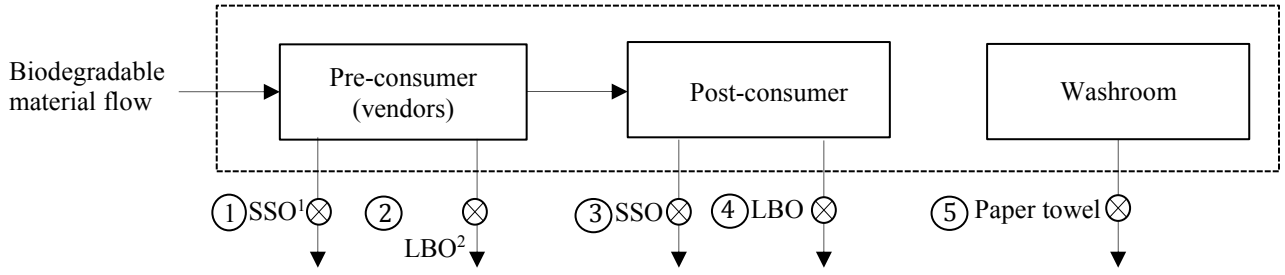
Building	Subcategory	Symbol	Sampling Frequency
Students' Union Building	1- Juicy 2- L'Express (LE) 3- Cram Dunk (CD) 4- Room at the Top (RATT) 5- Java Jive (JJ) 6- Taco Time (TT) 7- Edo Japan 8- Marco's Famous (MF) 9- Subway 10- Food waste and biodegradable fibers such as napkins (P (F+N)) 11- Washroom paper towels (P(P))	SUB	Two days
Faculty Club		FC	One day
Central Academic Building		CAB	One day
HUB International ***(commercial area only)***		HUB	One day
Education Centre North and South		ED	One day
Edmonton Clinic Health Academy		ECHA	One day
Lister Centre ***(commercial area only)***		LC	One day

Figure 2.1, Figure 2.2, and Figure 2.3 present simplified schematic diagrams of material flow through the food services buildings and identify locations used for collecting samples. As shown in Figure 2.1.a the SUB waste generators were divided in three categories: (1) pre-consumer (individual food vendors), (2) post-consumer, and (3) washrooms. The pre-consumer category was comprised of nine vendors: Juicy, L'Express (LE), Cram Dunk (CD), Room at the Top (RATT), Java Jive (JJ), Taco Time (TT), Edo Japan, Marco's Famous (MF) and Subway (Table 2.2). In pre- and post-consumers streams, the samples were collected from two sources: (1) source separated organics (SSO) and (2) landfill-bound organics (LBO). The SSO were collected from waste bins that were designated for organic material only. The LBO were collected from waste bins designated for the landfill. The organics were separated from the

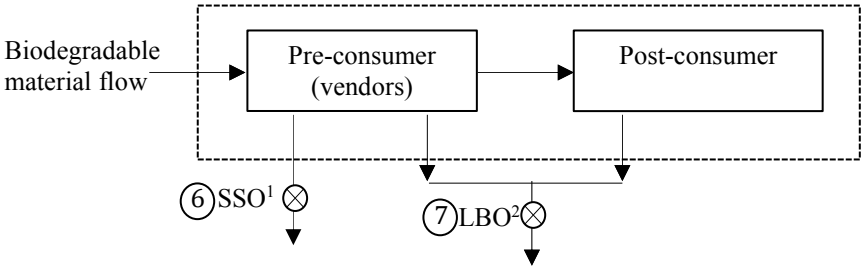
refuse bins by the waste sorters employed by the audit program. Paper towel is the sample collected from washrooms. Consequently, the sampling was conducted from five different points in SUB.

The sampling procedure was different in other food service buildings. Each building had two waste generators; pre-consumer and post-consumer and samples were collected from two locations (Figure 2.1.b).

a.



b.



Buildings boundary

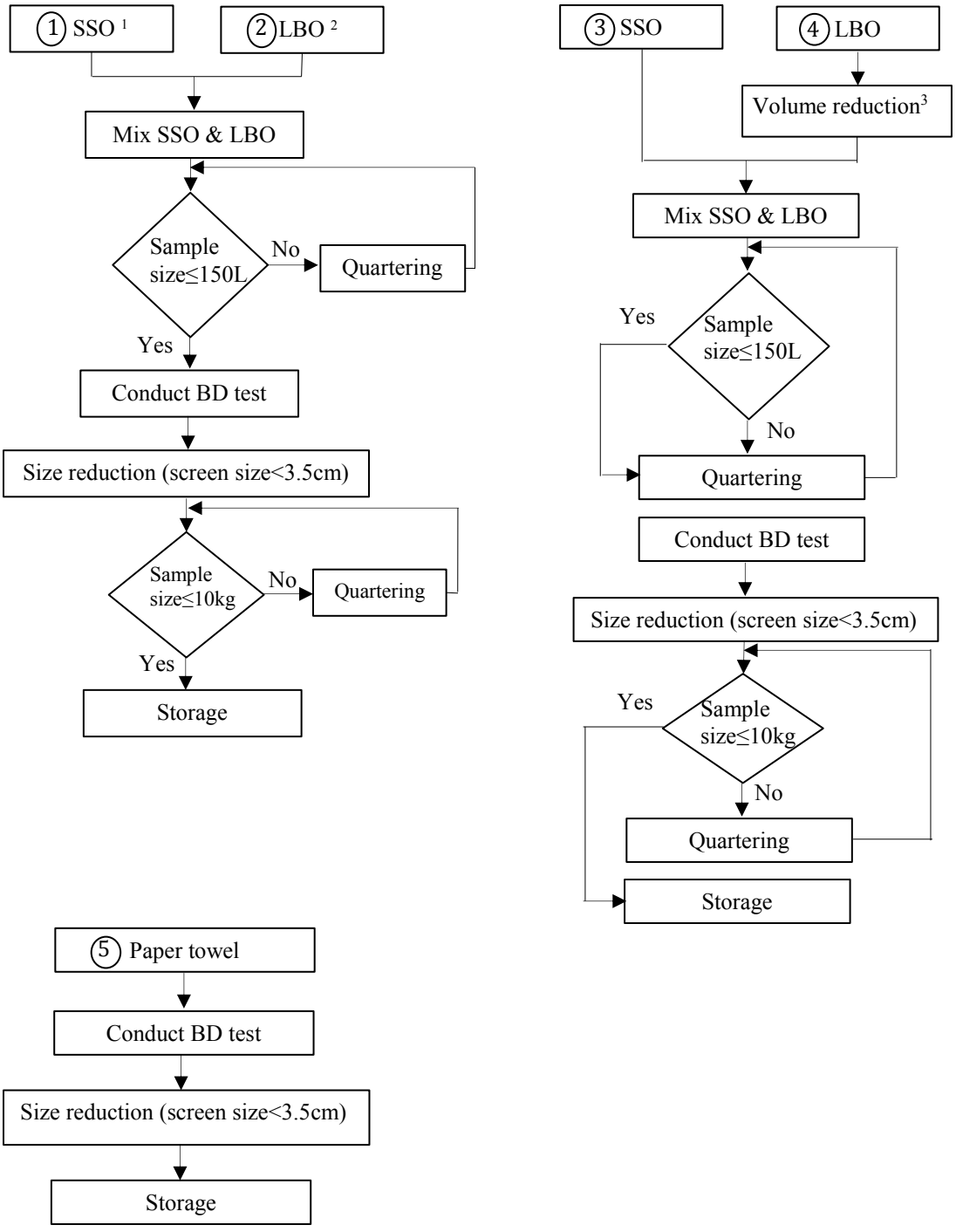
Sampling point

[1] source-separated organics, [2] landfill-bound organics.

Figure 2.1. Location of sampling points in: a. SUB b. food service buildings other than SUB.

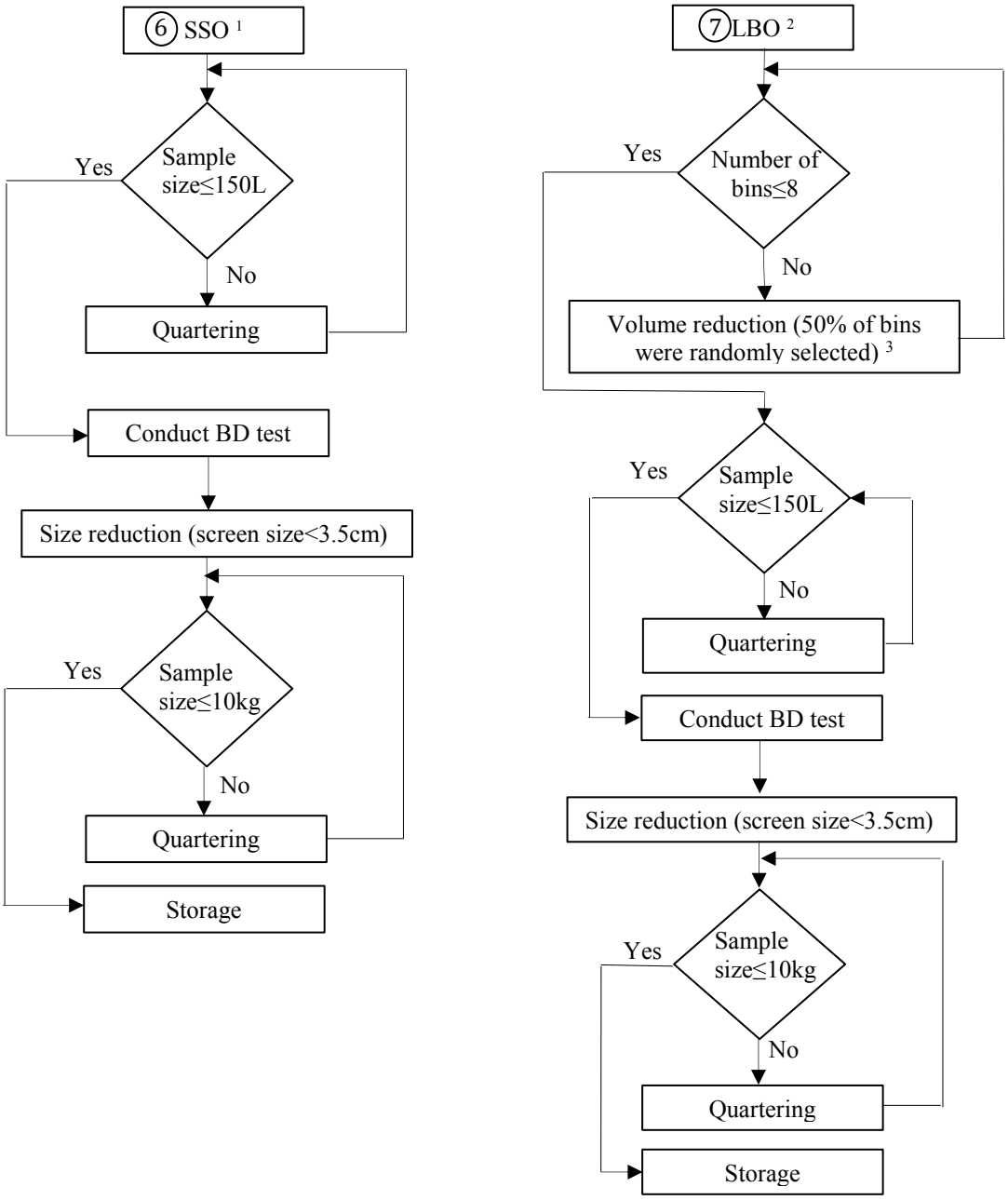
The amount of waste generated in each target building resulted in a different sampling methodology for each type of waste generator (pre-consumer, post-consumer and washroom). For example, in SUB, there were some sub-category samples in both pre-consumer and post-

consumer streams that contained a small amount of SSO. In fact, the sample was not enough to be analyzed regarding their physical and chemical characteristics. Therefore, in order to be consistent between the samples, where necessary, the LBO and SSO streams were mixed together. The samples were then size reduced by quartering method (ASTM C 702-98) to the desired sample size (≤150 litre) to conduct the bulk density (BD) analysis. The BD test was conducted in triplicate according to TMECC 03.01C. In the next step the samples particle sizes were reduced by a shredder (ECHO Bear Cat, SC3342) with the screen size of 3.5 cm. The shredded samples sizes were reduced to ≤10 kg by quartering method. A 10 kg sample was enough to conduct all the selected physical and chemical analyses in triplicate. The shredded samples were placed in the separate Ziploc bags for each analysis and stored in a freezer (-20^{o}C) until being characterized. Sample handling and processing flowcharts for SUB and washroom samples, were shown in Figure 2.2. In food services buildings other than SUB, the same procedure was applied (Figure 2.3); however, it was not necessary to combine the SSO and LBO samples.



[1]source-separated organics, [2] landfill-bound organics.
[3] Sample volume was reduced by randomly selecting 20% of bin content. To randomly select the bins, a number was assigned for each bin, and then the random numbers were generated using a calculator. The volume was reduced by taking out the bins that their assigned numbers were generated.

Figure 2.2. Details of sample handling and processing of SUB samples.



[1] Source-separated organics, [2] landfill-bound organics, [3] To randomly select the bins, a number was assigned for each bin, and then the random numbers were generated using a calculator. The volume was reduced by taking out the bins that their assigned numbers were generated.

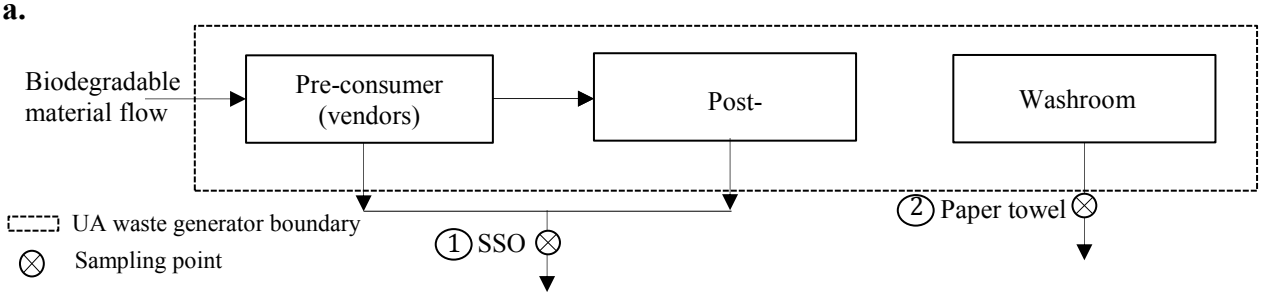
Figure 2.3. Details of sample handling and processing of samples in food service buildings other than SUB**.**

2.2.1.2 Biological test samples

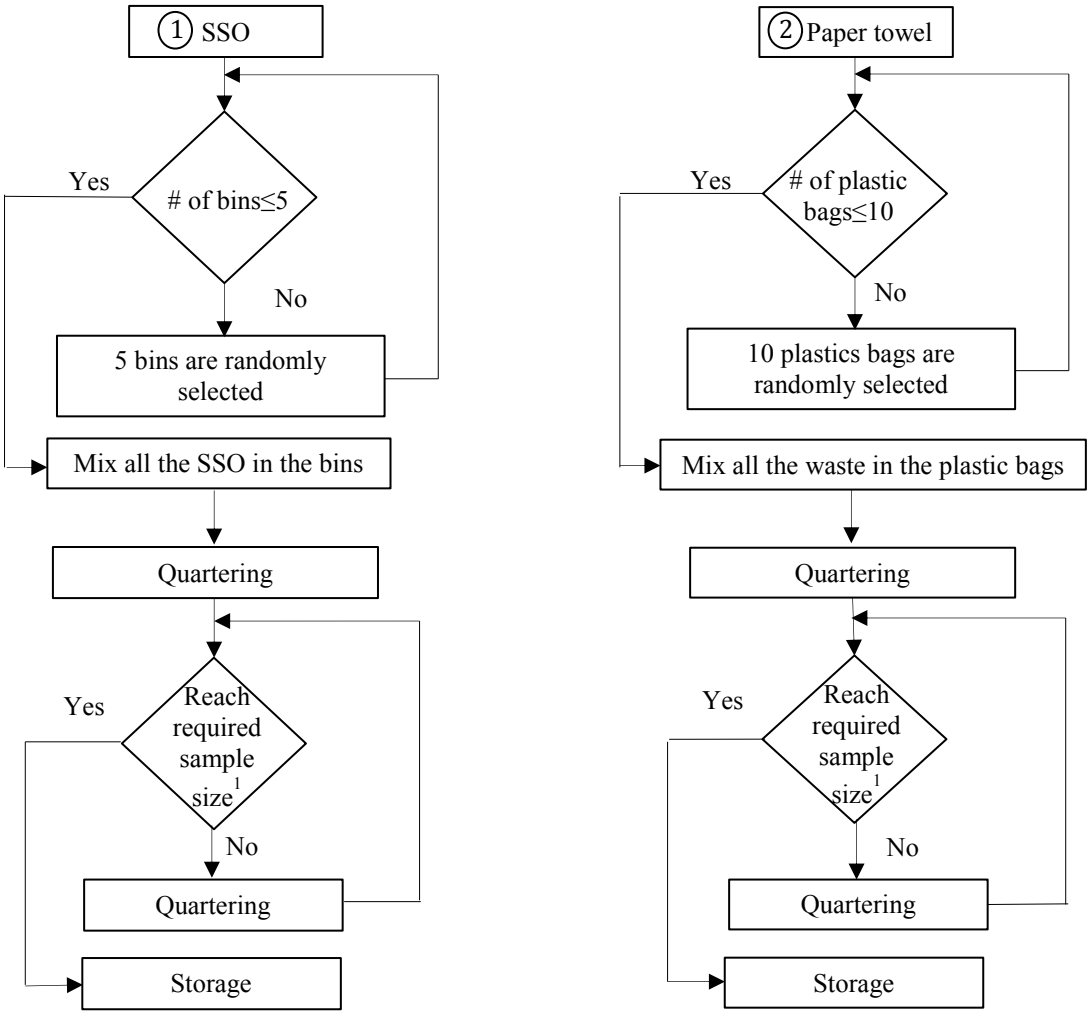
The approach to investigate the biological properties biochemical methane potential test (BMP) was slightly different from the physical and chemical tests. The BMP test was conducted on one composite batch of sample instead of running the test for every single sample (like physical and chemical tests). The composite sample was the mixture of representative samples collected from eight selected buildings. The same procedure of waste characterization sampling plan was followed to collect these samples. First the UAlberta buildings were grouped into four categories based on their functional use: (1) food services, (2) classrooms and offices, (3) residences and (4) labs. For each building category, two representative buildings were selected. The selection was based on assumed similarities in building activities. In each representative building, samples were collected from two streams (SSO and paper towel). SSO was the mixture of organics from pre and post-consumers. The required sample that needs to be collected from each building category was calculated based on the amount of total organics generated and organic compositions (the amount of SSO and paper towel). The location of sampling point is shown in Figure 2.4.a.

After collection of all required samples to conduct the BMP test, the samples were mixed based on the organics amount available in each building category and stored at 4 °C in the fridge before starting the test. The details of sample collection and processing are shown in Figure 2.4.b.

a.



b.



[1] Required sample size was different and based on the amount of total organics generated in each building.

Figure 2.4.a. Location and **b.** details of sample handling and processing for the BMP test.

2.2.2 Samples characterizations

The representative samples collected from UAlberta were characterized to determine their physical, chemical, and biological properties. All parameters except BMP were quantified in triplicate according to the standards presented in Table 2.3.

The biodegradability of samples was determined using BMP test as described in Angelidaki et al. 2009 study. The modified standard operation procedure is also presented in Appendix B2. The test was performed on duplicate batch cultures containing substrate, inoculum, and medium.

The inoculum was anaerobic digested sludge obtained from a full-scale anaerobic digester at the Gold Bar Wastewater Treatment Plant (WWTP) in Edmonton, Alberta, Canada. The medium was prepared based on the method proposed in (Angelidaki et al. 2009). The mixture was digested in 1-L batch reactor at a thermophilic temperature (55°C), with an ISR (inoculum to substrate ratio, VS based) of 2. A blank reactor contained only inoculum and medium was also incubated at the same temperature to correct the biogas generated from the mixture of inoculum and medium. Therefore, the results only represent the methane production from the substrate and not from the inoculum. After the mixture preparation, each reactor was flushed three times, three minutes each time with nitrogen gas to ensure anaerobic conditions in headspace of the reactor.

The methane production from each reactor was calculated based on the volume of the headspace of each reactor and the methane content measured using gas chromatography (Agilent 7890B) equipped with FID detector. The measured methane volume was adjusted to the volume at standard temperature (0 °C) and pressure (1atm).

Table 2.3. Physical, chemical and biological test and standard method used.

Analyses	Standard method
Physical tests	
Bulk density (BD)	TMECC 03.01A [a]
Moisture content (MC), Total solids (TS)	TMECC 03.09
Volatile solids (VS)	TMECC 05.07
Chemical tests	
pH	TMECC 04.11
C/N ratio	- [b]
Biological test	
Biochemical methane Potential (BMP)	- [c]

[a] (Thompson et al. 2001)
[b] C/N ratio was measured using a Leco TruSpec CN Analyzer according to the method specified by the manufacturer.
[c] There is no known standard method for the BMP test (Angelidaki et al. 2009). A brief description of the methodology used is presented in Appendix B.

2.2.3 Weighted-Average Calculation Method

After collecting samples and conducting physical and chemical measurements, a four-step approach was taken to determine weighted-average physical and chemical characteristics of organic material coming from the whole UAlberta campus.

The first step involved selecting representative samples for each building category. UAlberta buildings were grouped into five categories based on their functional use: (1) food services, (2) large classrooms, (3) small classrooms, (4) residences, and (5) labs. For each building category, the representative samples were selected based on the buildings sampled and analyzed (Table 2.4). The selection was based on assumed similarities in building activities. For example, the SUB building was considered as one of the representative samples for the food services category due to the large number of food vendors at its location. The second step involved estimating the characteristics of representative samples. The characteristics were calculated based on the physical and chemical tests results and the amount of organics collected from each building. In the third step, the characteristics of each building category were calculated. The characteristics in each building category were estimated by determining the average value of its representative samples. For example, the total solids value in the food services building category was the average total solids values from SUB, HUB, CAB, and LC. However, for the building categories with one representative sample, the value of that specified sample was used (e.g. for small offices category the value of sub-postconsumer was used). In the fourth and final step, the results of physical and chemical characteristics of each building category and the estimated amount of organics generated in each building category were used to estimate a total weighted average of physical and chemical parameters for the entire UAlberta campus. The sample calculation of the proposed method was presented in Appendix B1.

Table 2.4. List of UAlberta Building Category and representative samples.

Building category	Representative samples
1. Food services	SUB, HUB, CAB, LC
2. Large classrooms	ECHA and ED
3. Small offices	SUB post consumer
4. Residences	SUB post consumer
5. Labs	SUB post consumer

It should be noted that since the BMP test was conducted on a batch of samples (mixture of samples collected from all building categories), no additional calculations were required to determine the BMP value.

2.3 Results and discussion

2.3.1 Physical and chemical properties

A summary of the total weighted-average values of organic waste collected at UAlberta compared with results from other similar studies is presented in Table 2.5. The BD is a useful parameter in designing and determining volumes for on-site storage, hauling, and sizing of processing equipment. As shown in Table 2.5, the weighted-average value of BD was 344 kg m^{-3} and in the range of the other studies (269 to 552 kg m^{-3}). The BD values in this study ranged from 41 to 706 kg m^{-3}. This high variability was due to the different waste streams included in this study, e.g. food waste and paper towels. The wide range of BD reinforces the importance of appropriate sampling plan to collect the representative samples from the entire institution.

The total solids (TS) and volatile solids (VS) are two important test parameters for biological conversion processes. The TS of UAlberta's organic waste was in the range of 15%-67% with the weighted-average value of 33%, which was in the maximum level of reported range compared to the other studies. This was due to the composition of the organic waste collected in UAlberta. In the reviewed studies, organic wastes were mostly collected from food services and restaurants, which have a lower total solids and higher moisture content. However, in this study, the organic wastes were collected from both SSO (food services and restaurants) and LBO streams. Therefore, the high amount of biodegradable fibres (paper towels) available in LBO stream increased the overall weighted average value of the total solids. The volatile solids were also slightly high with respect to the reported range. Similar to total solids, the high value was due to the existence of biodegradable fibres in the collected organic wastes.

Table 2.5. Total Weighted-average Value of UAlberta and Overall Ranges in Other Studies.

Source of waste	Location	Wet BD (kg m^{-3})	TS (%)	VS (%TS)	pH	C/N (%TS)	Country	Reference
Organics	**Food services**	**344**	**33**	**94**	**4.1**	**19**	**Canada**	**Present study**
Food waste	University campus [a]	-	32.7	-	-	15.5	New Zealand	(Mason, Oberender & Brooking 2004)
Food waste	Commercial sectors [b]	-	30	80	-	14.8[c]	United States	(Zhang et al. 2007)
Food waste	University's cafeteria	-	20	94	5.12	-	Korea	(Kwon, Lee 2004)
Food waste	University's restaurant	-	20	-	3.5-4	7[d]	Korea	(Yun, Park & Park 2005)
Food waste	Commercial sectors [e]	269-552	11.1-13.7	-	3.84-4.55	19.1-29.3	Canada	(Adhikari et al. 2008)
Food waste	Commercial sectors [f]	-	31.4	73	4.5	20	Finland	(Himanen and Hänninen 2011)
SS-OFMSW[h]	Commercial sectors [g]	-	18.6-19.3	92.6-95.6	-	15-17	Lebanon	(Ghanimeh, El Fadel & Saikaly 2012)
SS-OFMSW	Various sources [h]	-	3.0-4.5	84.1-98.0	3.68-4.57	13.7-31.4	Italy	(Cabbai et al. 2013)
OFMSW	University's restaurant	500	-	69.8	4.5	37.8	Spain	(Forster-Carneiro et al. 2007)
Summary of other studies results		**269-552**	**3-33**	**70-98**	**3.5-5.1**	**7-38**		

[a] Kitchen/cafeteria and concourse areas of a university campus.
[b] Includes 300 restaurants, 50 food markets (grocery stores), and 150 commercial sources (hotels and businesses).
[c] C (total)= 46.78% (dry weight basis), N (total)= 3.16% (dry weight basis).
[d] 48.4% carbon and 6.9% nitrogen.
[e] Restaurant and a community kitchen in downtown Montreal, Canada from May to August 2004.
[f] The samples was collected for 3 days at the food catering centre of the town of Mikkeli (Finland).
[g] Source separated organic fraction of municipal solid waste.
[h] The SS-OFMSW was collected from restaurants and food markets.

The pH is a chemical property that affects microorganism activity and chemical speciation. Thus the pH value should be analyzed in preprocessing stage of AD processes. The acceptable enzymatic activity of anaerobic bacteria occurs in pH range of 6.2-7. In fact, the methane forming bacteria cannot be activated in pH below 6.2 (Gerardi 2003). The pH was in the range of

3.65-7.42, with the weighted-average value of 4.1. The observed pH values were lower than neutral range (6.2-7) and within the same range of the reported studies. The low pH in this study reinforces this fact that the biological process happened during on-site storage of waste that can lead to anaerobic conditions and production of volatile fatty acids that leads to a drop in pH.

The C/N ratios were in the range of 9-46 and within the range of the reported studies (7-38). C/N ratio is an important parameter, which should be taken into consideration in the design of any biological process. Suitable balance between the carbon and nitrogen in the feedstock improves the decomposition of the organic material, while unsuitable range may cause high total ammonia nitrogen (TAN) production leading to high VFA accumulation. Many articles suggested the range of 20-30 for C/N ratio as an optimum range for microbial growth (Álvarez, Otero & Lema 2010, Brown, Li 2013, Li, Park & Zhu 2011). The weighted average value of C/N ratio at UAlberta was 19, in the low level of acceptable range.

2.3.2 Biological property

The methane yield ($mLCH_4\ g^{-1}$ VS) results from the BMP test are shown in Figure 2.5.a. The results only represent the methane production from the substrate since the methane generated in the control reactor (mixture of inoculum and medium) was subtracted from the methane generated in the mixture of substrate, inoculum, and medium. The overall methane yield was 357 $mLCH_4\ g^{-1}$ VS. Approximately 80% of methane was achieved during the first 12 days of digestion.

The biogas compositions for both sample and controls are shown in Figure 2.5.b. The highest methane concentration of the sample was also achieved after 12 days with the value of 64%, while this amount was only 13% for the control at the same day. The BMP values reported in the literature had a wide range of 99-675 $mLCH_4\ g^{-1}$ VS (Cabbai et al. 2013). Lack of one single standard protocol and use of non-standardized inoculum makes the comparison difficult among the results of different studies. However, in a similar BMP test condition (reactor size and thermophilic condition), Zhang et al. (2007) reported a range of 425-445 $mLCH_4\ g^{-1}$ VS. A little higher BMP value found in Zhang et al. (2007) study is probably due to the sample composition. In this study the sample was prepared from the mixture of food waste and biodegradable fiber

(paper towel). Presence of fiber in the samples may cause in decreasing of the BMP value since it is not easily degradable, while the sample used in Zhang et al. (2007) study was mainly comprised of food waste.

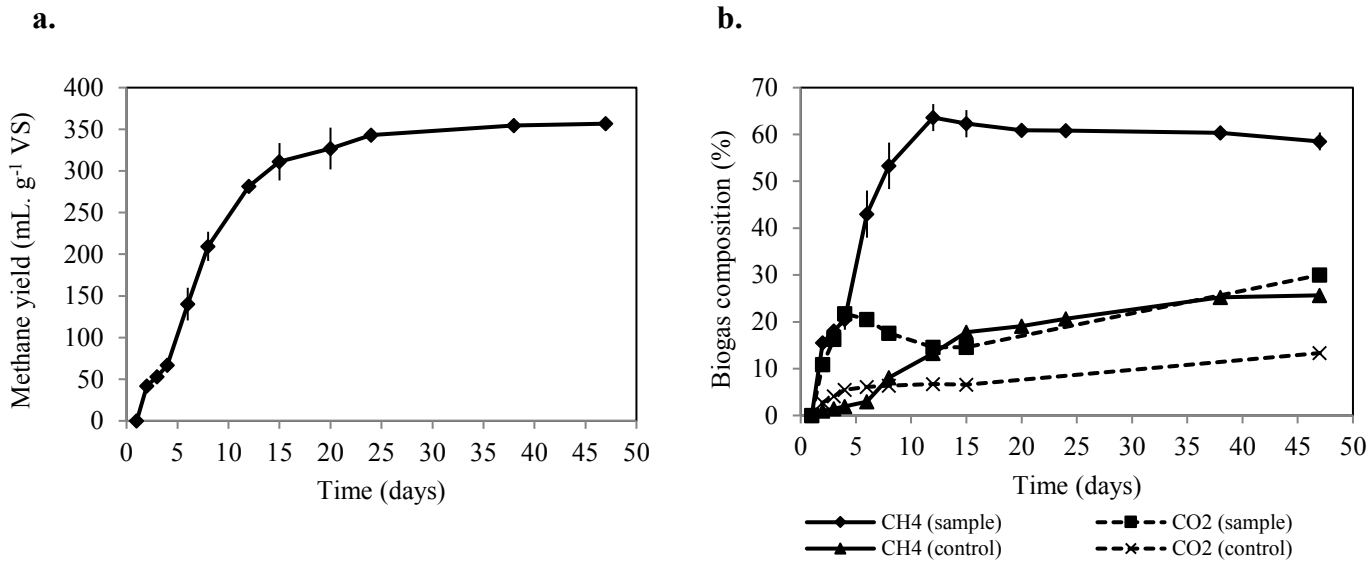


Figure 2.5. **a.** Methane yield and **b.** Biogas composition during BMP test.

2.3.3 Sampling methodology discussion

Although institutional waste quantities were investigated in many studies (Ishak, Mahayuddin & Mohamed 2015, Smyth, Fredeen & Booth 2010, de Vega, Benítez & Barreto 2008, Mason, Oberender & Brooking 2004, Zhang, Lee & Jahng 2011, Zhang et al. 2011), waste quality studies are not as common.

To estimate the quality of the UAlberta organic waste stream, a waste audit (characterization) sampling methodology was used to collect samples. Representative buildings were selected and categorized based on their functional uses. The advantage of this method of sampling is that the collected samples can be representative of the entire campus since it represents buildings with different functional uses. It would also be cost effective because rather than collecting samples from every single building in the whole campus, samples are only collected from the representative buildings. The weighted-average approach was applied to estimate the quality (physical and chemical characteristics) of UAlberta organic waste stream.

Since this method follows weighted-average approach, a waste characterization study that quantifies the amount of waste was required to use this method. Combining the quality study with the waste characterization resulted in an overall reduction in effort and cost of sampling.

Like any other sampling plan, weighted-average approaches have limitations. One of the limitations of this case was that the weighted-average approach cannot be applied to all analytical parameters – in this case bulk density and pH. Therefore, if deemed important, it is recommended to prepare a composite single batch from all buildings and conduct the analyses on the batch. The composite batch is a mixture of all representative samples prepared based on their quantitative data. Conducting analyses on a composite batch can also minimize the efforts and costs of the waste characterization. The BMP test in this study was conducted on the composite batch sample prepared by collecting the representative samples from each building category and mixing them all based on the available quantification data (waste audit results).

2.4 Summary and conclusions

For any institution, to develop or to further a waste management program, characterizing the quantity and quality of waste material is important. Although waste characterization in terms of waste quantity was investigated in many HEI's, the quality of waste align with the appropriate sampling methodology has not been studied widely.

In terms of quality parameters, organic waste collected from University of Alberta was characterized regarding its physical, chemical and biological characteristics. Two different samplings methodologies and calculations were applied; one to determine physical and chemical properties and the other one to investigate the biological properties. A portion of the sampling program was integrated into a waste characterization study. Representative samples were collected during the waste characterization study.

In the first sampling methodology the analyses were conducted on each collected sample and the characteristics in each building category were estimated by determining the average value of its representative samples. At the final step, the results of physical and chemical characteristics of each building category and the estimated amount of organics generated in each

building category were used to estimate a total weighted average of physical and chemical parameters for the entire UAlberta campus.

In the second sampling methodology, the analysis (BMP test) was conducted on a composite sample. The composite sample was the mixture of representative samples collected from selected buildings. The required sample that needed to be collected from each building category was calculated based on the amount of organics generated in each building. Conducting the test on a composite sample minimized the effort, time and cost required to conduct the analyses and also no additional calculations were required to determine the final value.

The proposed sampling methodology in this study can align with typical waste audit (characterization) studies at any HEI. The sampling program for waste characterization can be defined based on the quantification results achieved from the waste audit.

Regarding the waste quantification, the weighted average values of TS and VS of the sample collected at UAlberta were 33% and 94%, respectively. The representative sample had a pH value of 4.1 and C/N value of 19. The result of BMP test showed that almost 80% of methane was achieved during the first 12 days of digestion and the overall methane yield after 47 days was 357 $mLCH_4\ g^{-1}$ VS. In conclusion, the organic waste collected from HEI's can be considered as an appropriate feedstock for anaerobic digestion and would need to be mixed with bulking agents if it was to be used as a composting feedstock.

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CHAPTER 3: BENEFITS TO DECOMPOSITION RATES WHEN USING DIGESTATE AS COMPOST FEEDSTOCK: PART I - FOCUS ON PHYSICOCHEMICAL PARAMETERS[2]

3.1 Introduction

The organic fraction of municipal solid waste (OFMSW) is a significant portion of solid waste streams around the world. The interest in organic waste treatment has increased in recent years. Among the treatment technologies, anaerobic digestion (AD) has gained a significant role in municipal solid waste management due to its energy recovery benefits (Liu et al., 2012, De Baere, 2008). AD is the biological decomposition of organic waste streams in the absence of oxygen. The final products are biogas and digestate (Hilkiah Igoni et al., 2008). Biogas typically contains 60% to 70% methane (by volume), 30% to 40% carbon dioxide and minor quantities of nitrogen, hydrogen, ammonia and hydrogen sulfide (usually less than 1% of the total gas volume). Digestate is the solid residues generated from the biodegradation of organic waste during the anaerobic digestion process. It is a valuable soil conditioner; however, this high moisture content by-product is not fully stabilized, and when applied to land as a fertilizer, there is an increased risk of odour complaints, potential for phyto-toxic responses, and some difficulties in handling the materials (Teglia et al., 2011). Therefore, management of a high volume of digestate is one of the challenges that AD plants currently face.

Composting is typically used to improve digestate quality. Post treatment of digestate in a composting process can assure the maturity and stability of this by-product. The digestate from the AD process can also be mixed with fresh and/or stabilized organic waste and then fed to the composting process. However, co-composting of digestate has not been significantly investigated

[2] A version of this chapter has been submitted as: Arab, G. and McCartney, D. "Benefits to Decomposition Rates When Using Digestate as Compost Feedstock: Part I - Focus on Physicochemical Parameters" in the *Waste Management*.

in the literature, and there are still some concerns regarding the co-composting of the digestate with the organic waste in the composting process.

There are potential advantages of co-composting OFMSW and digestate, e.g. digestate can improve the physical properties of the composting process by providing moisture for low moisture content compost feedstock and vice versa, i.e. the fresh OFMSW may negate the need to dewater the digestate. The extra energy in the undigested material generates heat that helps to dry and stabilize the mixture; therefore, excess wastewater may not be produced (De Baere, 2008). Digestate also provides reliable nutrient sources such as nitrogen and phosphorus as well as micronutrients that may help increase feedstock stabilization rates. In addition to physicochemical property enhancement, the presence of mutual microorganisms in both AD and composting material, may have positive interaction effects – the digestate could be considered an inoculum to the composting process (Ryckeboer et al., 2003; Partanen et al., 2010). Although composting is an aerobic process, the presence of anaerobes is inevitable, even at well managed facilities (Ryckeboer et al., 2003). With respect to the presence of common microflora in composting and AD processes, composting inoculation with digestate can alter the microbial interactions (e.g. mutualism and antagonism) and possibly enhance the composting process. However, in order to benefit from composting inoculation, the quantity of inoculum should be carefully investigated. The quantity of inoculum introduced to the compost must be sufficient, otherwise the indigenous microorganisms in compost may not allow the inoculum microflora to develop and effectively influence the process (Fuchs, 2010; Golueke et al., 1954). Composting inoculation with digestate can also be more economically beneficial compared to direct microbial inoculation because, in this method, instead of purchasing or preparing the specific type of microbe, the waste is co-composted with another type of waste that already contains various microbial communities. Therefore, not only does the composting process benefit from the inoculation but also the inoculant (waste) is undergoing further treatment process.

Considering all the stated advantages of co-composting of digestate and organics, the objective of this study was to determine if different ratios of digest to fresh feedstock would impact stabilization rates. The study was divided into two parts: (1) effects of physicochemical parameters on stabilization rates that are discussed herein; and (2) effects of biological characteristics and microbial population on stabilization rates.

3.2 Materials and methods

To investigate the effects of adding digestate into the composting process, the experimental run was conducted in three steps. In the first step, digestate was prepared in a high solids anaerobic digestion (HSAD) process. In the second step, prepared digestate was mixed with the fresh compost feedstock with different mix ratios (%w/w) and aerated for thirty days. Finally, in the third step, the stabilized compost was cured for two months. The overall diagram of material flow and process used in this study is shown in Figure 3.1.

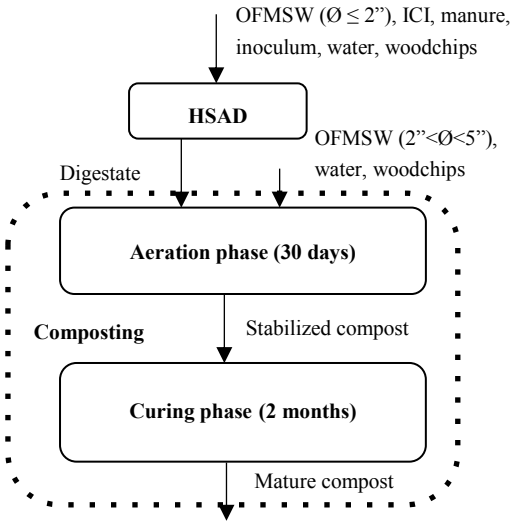

Figure 3.1. Process & material flow used in research.

3.2.1 Anaerobic digestion equipment

The digestate was prepared at the Alberta Innovates – Technology Futures (AI-TF) laboratory using their high solids anaerobic digestion (HSAD) pilot-scale facility in Vegreville, Canada. The HSAD set-up consists of two stainless steel dry digesters (primary digester and percolate digester) with working volumes of 500 L and 150 L, respectively. The digesters were automated with gas production, gas composition, pH, and temperature measurements. The anaerobic digester photo is shown in Appendix A, Figure A2.

3.2.2 Anaerobic digestion feedstock

Two consecutive HSAD batches were processed to prepare the digestate. The first batch generated digestate inoculum for the second HSAD feedstock batch. In the second batch, about 45% (wet mass) of the digestate inoculum prepared in the first batch was mixed with fresh feedstock.

The anaerobic digester feedstock recipe was prepared to align with the expected full-scale feedstock to be used by the City of Edmonton (CoE). Feedstock consisted of three streams in both batch 1 and 2 of the AD process: (1) organic fraction of municipal solid waste (OFMSW) with a particle size of <2" collected from the Integrated Processing and Transfer Facility (IPTF) in CoE; (2) source separated organics (SSO) collected from institutional, commercial and industrial (ICI) sectors; and (3) horse manure collected from one load from the stable that delivers their manure to the IPTF (mixture of horse manure, urine, and sawdust). Inoculum was also added to batch 1 that was composed of a mixture of beef feedlot manure and wheat straw. The sampling methodology to collect SSO is explained in Appendix C.

In addition to these four streams, woodchips were also added to the feedstock as an amendment. The woodchips used in batch 1 were collected from the Construction and Demolition (C&D) waste pile at the CoE with a mixture of painted and white woodchips with the particle size of 6 to 8 inches. For batch 2, the woodchips were collected from the green wood chips pile at the CoE and the particle size of 0.79 inches (20 mm) and smaller were screened out. Water was also added to adjust the total solids of the digester to the range of 30-35%.

The composition and amount of the materials used in the first and second batches of the dry digester are listed in Table 3.1.

Table 3.1. Composition and amount of the materials in the anaerobic digestion batches.

Material	Batch 1	Batch 2	Batch 1	Batch 2
	% (wet weight basis)		kg (wet weight basis)	
OFMSW	32.6	22.9	105.8	100.9
ICI SSO waste	29.4	20.7	95.3	90.9
Horse manure	0.6	0.5	2.1	2.0
Inoculum[a]	5.6	45.4	18.1	200.0
Wood chips	3.5	2.6	11.4	11.3
Water	28.2	8.0	91.3	35.1

Note: [a] Batch 1 consisted of beef feedlot manure and wheat straw and batch 2 consisted of digestate prepared in the first batch.

3.2.3 Composting equipment & operation

The composting experiment was conducted in two phases to simulate the composting process in the full-scale operation. In the first, high rate phase, the materials were aerated in eight different reactors for 30 days. Each reactor was air tight with a working volume of 25 L. The schematic of an individual reactor is shown in Figure 3.2 and the picture of the composter reactor with associated apparatus is shown in Appendix A, Figure A1. After 30 days of aeration, the materials were transferred to another type of reactor (not air tight) to simulate the curing phase of the composting process and the curing phase was monitored for two months, until all reactors reached the maturation criteria. The reactors used in the curing phase were 20 L pails with perforated ends on the bottom and top to allow natural ventilation.

During both high-rate and curing phases, each reactor was insulated with 5 cm of thick pink fiberglass and an aluminium-reflecting blanket in order to minimize the heat loss. The insulated reactors were then placed in a temperature-controlled chamber. Each reactor was equipped with a thermocouple (HSTC-TT-K-24S-120-SMPW-CC). At start-up of the experiment, the temperature control chamber and reactors were at room temperature. During the high rate phase, the temperature of each reactor was recorded every ten minutes. Each day the chamber temperature was adjusted to 5 °C below the temperature of the reactor with the lowest temperature to minimize the heat loss caused by temperature gradient between reactors and chamber. However, during the thermophilic phase of run when the temperature of any reactor

increased above 65 °C, the chamber temperature was reduced to maintain temperatures below 65 °C in the reactors.

During the curing phase, the chamber temperature was set at 24 °C. Compressive loads were applied to each reactor to simulate the compressive settlement existing in the full-scale aeration bays. The weight used varied in each reactor and was calculated based on the bulk density of the substrate in each of the reactors. The simulation height was 1.6 m, which is the middle height of the aeration bays in the Edmonton Composting Facility (ECF).

During the high-rate phase, air was supplied to each reactor to ensure oxygen was not the limiting reactant and also to cool down the temperature inside the reactors, in case the temperature was higher than 65 °C. The air was supplied using an aluminium tank air compressor (1.0 HP, 1.6 Gal, 1610A). The input air was pre-conditioned by passing through a humidifier.

During the curing phase, forced aeration was not used; however, the perforated plates on both ends of the reactors allowed natural ventilation. Turning frequency was two times a week and once every 35 days during the aeration phase and curing phase, respectively. At each turning day, each compost reactor's material was thoroughly mixed after unloading and the representative samples were obtained by mixing sub-samples taken from different points (top, bottom, middle and corners) of the bulk material.

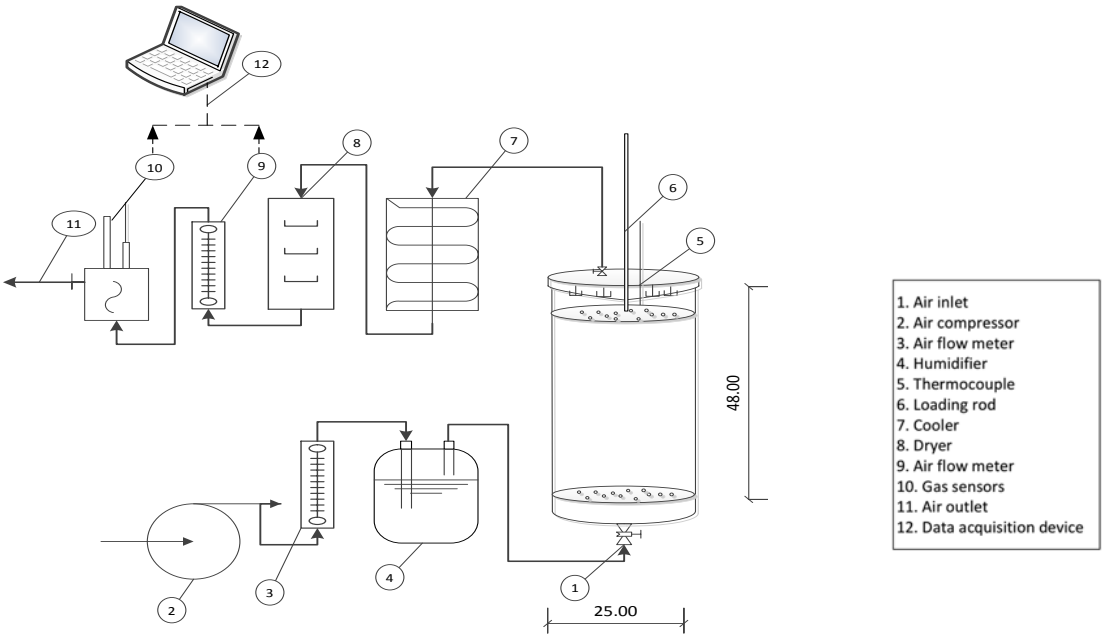

Figure 3.2. Schematic of a reactor in active aeration phase.

3.2.4 Composting feedstock

The two main feedstocks to the co-composting reactors were the OFMSW and the digestate that were mixed in eight different ratios. The OFMSW was prepared from material collected during five working days in the CoE's IPTF during the spring of 2015. The material consisted of kitchen waste, yardwaste, grass, and thatch. The material also had a larger particle size (2 to 5") as compared to the OFMSW (<2") collected as AD feedstock. The digestate was supplied from the pilot-scale HSAD as described previously. Both OFMSW and digestate were characterized for physico-chemical characteristics. To compare variations between two feedstocks, a two tailed *t*-test was applied for each dependent parameter presented in Table 3.2. A *p*-value below 0.05 was considered statistically significant.

Table 3.2. Characterization of co-composting reactor feedstocks: OFMSW and digestate.

Parameter	OFMSW[1]	Digestate[1]	n[2]	*p*-value
Bulk density (kg. m^{-3})	170±12	790±48	3	<0.01
Total solids (%)	58±1	37±2	3	<0.01
Volatile solids (%DM)	74±7	48±4	3	0.03
pH	6.1±0.11	8.5±0.05	3	<0.01
EC (μS. cm^{-1})	875±33.23	1075±8.49	3	<0.01
Total carbon (%DM)	36.0±0.5	24.5±1.8	2	0.03
Total nitrogen (%DM)	1.44±0.08	1.60±0.10	2	0.35
Ca (g. kg^{-1} DM)	18.98±1.01	26.52±4.82	2	0.16
Fe (g. kg^{-1} DM)	3.45±0.27	4.84±0.39	2	0.05
Mg (g. kg^{-1} DM)	2.04±0.08	2.59±0.46	2	0.24
K (g. kg^{-1} DM)	5.77±0.03	10.50±0.30	2	<0.01
Na (g. kg^{-1} DM)	3.78±0.38	3.92±0.60	2	0.81
P (g. kg^{-1} DM)	1.99±0.29	1.54±0.24	2	0.23
S (g. kg^{-1} DM)	2.42±0.15	5.50±0.89	2	0.04
Mn (mg. kg^{-1} DM)	135.56±26.23	98.22±23.25	2	0.27
Zn (mg. kg^{-1} DM)	81.56±6.42	113.79±9.45	2	0.06
Cu (mg. kg^{-1} DM)	49.93±0.18	199.44±32.66	2	0.02
NH_4 (mg. kg^{-1} DM)	879±45	6197±88	2	<0.01
NO_3 (mg. kg^{-1} DM)	5.12±0.15	4.21±0.24	2	0.05

[1] Mean ± one standard deviation.
[2] Number of samples.

After collection and preparation of the two main feedstocks, eight different mixtures were prepared with the digestate portion of the feedstock equalling 0, 10, 20, 30, 40, 50, 75, or 100% (wet mass). Woodchips and water were then added as amendments to modify the physical properties (free air space (FAS) and moisture content (MC)) as needed. FAS calculation is explained in Appendix C. In order to have the optimum microbial performance during the composting process, it is suggested to adjust the MC and FAS to within the range of 50-65% and higher than 30%, respectively (Christensen, 2011; Alburquerque et al., 2008). The amounts of material used in each reactor are presented in Table 3.3.

Table 3.3. Composition and amount of the materials in the reactors.

Reactor ID	Digestate (%, ww[1])	OFMSW (%, ww)	Digestate (kg, ww)	OFMSW (kg, ww)	Water (kg)	WC [2] (kg)	Start-up mass (kg)
C0	0	0	0	4.24	1.22	0	5.46
C10	10	90	0.44	4.00	1.04	0	5.48
C20	20	80	1.06	4.26	1.02	0	6.34
C30	30	70	1.96	4.56	1.04	0	7.56
C40	40	60	3.71	5.57	1.00	0	10.28
C50	50	50	4.62	4.62	0.50	0	9.74
C75	75	25	8.42	2.81	0.00	0.59	11.82
C100	100	0	8.87	0.00	0.00	1.57	10.44

[1] Wet weight.
[2] Woodchips.

3.2.5 Analytical methods

The analyses conducted during the experiment were categorized into three main groups: (1) feedstock characterization; (2) process monitoring; and (3) stability and maturity indices. Parameters used to characterize the feedstock mixtures were: free air space (FAS), bulk density (BD), moisture content (MC), total solid (TS), organic matter (OM), pH, electrical conductivity (EC), and temperature. Process monitoring focused on temperature, MC, TS, OM, pH, and EC. Stability and maturity indices were tracked to determine time to composting process completion targets. The target end points were selected to correspond to the full-scale operational practices at the CoE's facility. The stability/maturity end points used by the CoE were respirometry and Solvita® tests. In this experiment, in addition to the respirometry and Solvita® tests, C/N ratio, and ammonium and nitrate analyses were also selected according to the Canadian Council of Ministers of Environment (CCME, 2005) and the California Compost Quality Council (CCQC, 2001) because measuring two or more parameters is recommended for stability/maturity measurement to have more accurate and reliable results (Wichuk and McCartney, 2010).

During the high-rate composting phase, each reactor was sampled twice per week. During a sampling event, each reactor's material was mixed after unloading. The analyses were performed on representative samples obtained by mixing sub-samples taken from different points (top, bottom, middle, and corners) of the bulk material. During the curing phase, the reactors were

sampled once every 35 days because of the slow rate and minor changes in the monitored parameters. The list of all selected analyses, number of replicates and their test methods are presented in Table 3.4. Each analysis method is given in the following paragraphs.

Before start-up of the composting experiment, the free air space (FAS) and MC of each mixture was determined and adjusted as needed. FAS was calculated from the BD (wet basis) value according to the following equation (Agnew et al., 2003): FAS (%) = 100-0.0889BD. The measurement apparatus used to determine the FAS was shown in Appendix C, Figure C6.

pH and electrical conductivity (EC) were determined on a feedstock slurry of 1:15 (feedstock: water), wet mass basis. Total carbon and total nitrogen of oven-dried samples were measured using a Leco TruSpec CN Analyzer according to the method specified by the manufacturer. However, the carbon analysed by the instrument represents the total carbon. It should be noted that wood chips added to C75 and C100 reactors to amend the free air space were removed prior to the C:N analysis.

The temperature in each reactor and chamber was recorded in ten-minute interval (the average of ten readings) during the experimental runs. The temperature data were used to create relative heat generation (RHG) values (Larsen and McCartney, 2000). The RHG value was calculated using the following equation:

$$\mathrm{RHG} = \int_0^t (\mathrm{T_{reactor}} - \mathrm{T_{chamber}}).\,\mathrm{dt}$$

where $T_{reactor}$ and $T_{chamber}$ are the reactor and chamber temperatures (°C), respectively and t is the duration of the experiment (hour). Respirometry was conducted using a Micro-Oxymax (ER-10) respirometer based on TMECC 05.08-A method (TMECC, 2002). The user manual of the instrument is presented in Appendix C. The specific oxygen uptake rate (SOUR) was calculated based on the average value of the instantaneous respiration taken during the 24 h of the most intense biological activity (Adani et al., 2004). Solvita® stability and maturity tests were conducted at room temperature for four hours according to the instruction manual (Woods End, 2002). Ammonium nitrogen and nitrate nitrogen was extracted with a 2 M KCL in a 1:10 (w/v, sample/extractant) and analyzed with a WestCo SmartChem 200 Discrete Analyzer (O'Dell, 1993). Nutrient contents (Ca, Fe, Mg, K, Na, P, S, Mn, Zn and Cu) were measured by

inductively coupled plasma-optical emission spectroscopy (ICP-OES, iCAP 6000 Thermo Fisher Scientific. 2007 Cambridge, UK) following HNO_3 digestion.

Table 3.4. Test methods used and stability and maturity end points targets.

	Parameter	Units	Stable/mature[1]	n[6]	Test method
Monitoring	BD	$kg.m^{-3}$	NA[2]	3	TMECC 03.01A
	TS	%, ww	NA	2	TMECC03.09
	OM	%, dw	NA	2	TMECC05.07
	pH	Unitless	NA	2	TMECC 04.11
	EC	$\mu s.\ cm^{-1}$	NA	2	TMECC 04.10
	Temperature	°C	<8[3]	-	-
Stability	C/N	Unitless	<25	2	-[4]
	SOUR	mg O_2.g^{-1} OM. d^{-1}	3-10	1	TMECC 05.08-A
	Solvita® CO_2	Solvita color code for CO_2	5-6	1	TMECC 05.08-E
Maturity	Solvita® NH_4	Solvita color code for NH_4	4	1	TMECC 05.08-E
	NH_4	mg NH_4. kg^{-1} dw	<500	2	NRAL-105[5]
	NH_4/NO_3	Unitless	<3	2	NRAL-105

[1] stability and maturity parameter values were adopted from CCQC (2001) and TMECC (2002, 2005).
[2] Not applicable.
[3] Temperature changes.
[4] The C/N ratio measured using a Leco TruSpec CN Analyzer according to the method specified by the manufacturer.
[5] Method NRAL-105 used for the extraction and NH_4 & NO_3 were analyzed according to the method specified by the manufacturer (WestCo SmartChem 200 Discrete Analyzer).
[6] Number of samples.

3.3 Results and discussion

In this section the typical performance parameters (temperature, RHG, ROR, and SOUR), and chemical parameters (initial C/N ratio and total C_{bio}, trends of inorganic nitrogen, pH, EC, and Solvita®) will be presented and then the effects of digestate ratio on biological activities during composting and possible effects of OFMSW on digestate composting will be discussed. At the end of this section the possible benefits of OFMSW on digestate during composting were explained.

3.3.1 Typical performance parameters

Temperature, OM removal, and SOUR values are major performance indicators in the composting process as they are all related to substrate biodegradation rates. Representative trend graphs of temperature, relative heat generation (RHG), relative OM removal (ROR), and SOUR values, for three reactors are shown in Figure 3.3. The RHG values were calculated from the temperature differences between the reactors and the environmental chamber, as previously described. ROR is defined as the total OM removed during composting per OM added at the first day of loading in each reactor. The SOUR values were obtained by running the respirometry test. Typically, reactors C20, C30, and C40 behaved better than the other reactors. Therefore, for clarity, trends of C40 and the two controls (C0 and C100) were presented in the following graphs. The trends of all other reactors were presented in Appendix C. It should be noted that since the RHG, ROR, and SOUR changes during the curing phase (day 30 to 100) were small, especially after day 70, only the first 70 days of composting were presented.

During the first week of operation, the temperature rose rapidly, exceeding 60 ºC and the RHG values reached 36-43% of total values among all the reactors. Heat generation strongly correlated with ROR (R^2=0.93-1) in all of the reactors. As composting proceeded, the OM stabilized and the decomposition rate reduced; therefore, the heat generation and oxygen uptake rate progressively declined.

In C75 and C100, SOUR values showed an increase in respiration rates on day 3 as compared to day 0 (C75 SOUR value on day 0 and 3 can be found in Appendix C, Table C32 and Table C33, respectively). This was probably caused by temporarily inhibition and/or longer lag phase. Both of these reasons were probably related to the high amount of digestate in these two reactors. Temporary inhibition could be due to high ammonium content available in the digestate. A longer lag phase could also happen because the main portion of the microorganisms in C75 and C100 were anaerobic consortia. A similar trend for the respiration index of bio-stabilized municipal solid waste was observed by Adani et al. (2004).

To investigate compost stability and material retention time (MRT), the SOUR values were compared to end-point standards. MRT was defined as the day at which each reactor reached the stability end point. TMECC 05.08 (2002) suggested the stability threshold of $<10 mg\ O_2.g\ OM^{-1}$.

d^{-1} (≈ 400 mg O_2.kg OM^{-1}. h^{-1}) for stable compost. In order to estimate the MRT, the respirometry data were interpolated. The results showed 400 mg O_2.kg OM^{-1}. h^{-1} was achieved after 23-26 days in C20, C30 and C40; after 27-29 days in C75 and C100; after 34 days in C50; and after 36-37 days in C0 and C10. These observations were consistent based on the results obtained from ROR and RHG parameters. Among the reactors, C20, C30, and C40, with higher ROR and RHG values, reached the maturity end point in a shorter period of time. The shorter MRT in C75 and C100 compared to C0 and C10 can be explained by the fact that the digestate, the main feedstock in C75 and C100, had been partially stabilized during 42 days in the anaerobic digestion run. Reactors C20 to C40 reached the end points 30 to 36% faster than the C0 (the control).

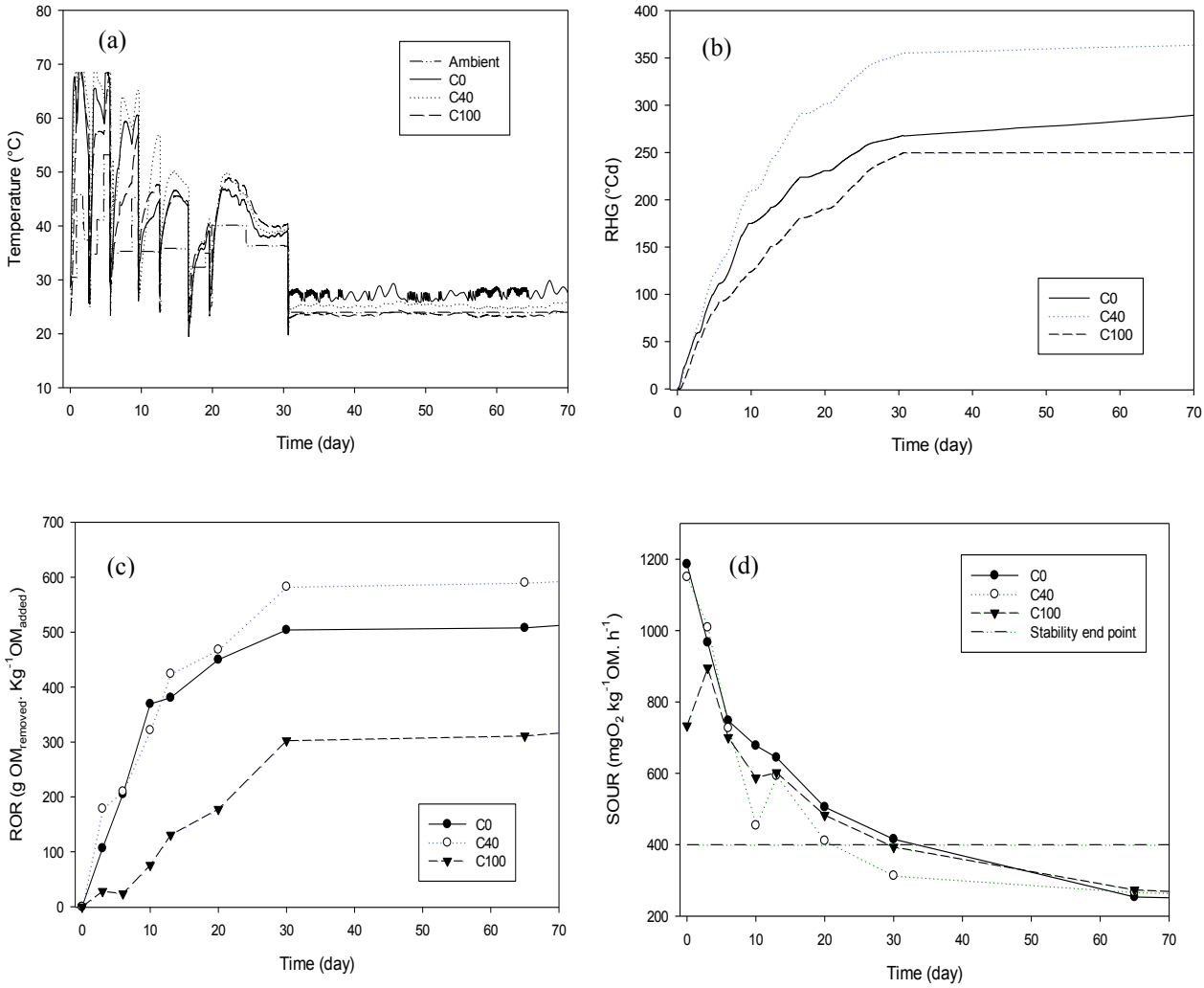

Figure 3.3. (a) Temperature, **(b)** Relative heat generation (RHG), **(c)** Relative OM removal (ROR) and, **(d)** Specific oxygen uptake rate (SOUR) during composting.

3.3.2 Initial C/N ratio

While it is common to represent C/N ratio values using total carbon data, in this study the C/N ratio is presented in two forms; total carbon to nitrogen ratio (C_t/N) and biodegradable carbon to nitrogen ratio (C_{bio}/N). C_{bio} value was calculated based on the actual carbon degraded during the 100-day experimental period. The results are presented in Appendix C, Table C58. It was assumed that all forms of nitrogen were bio-available (Haug, 1993).

The initial C_t/N and C_{bio}/N in all eight reactors are shown in Figure 4. As shown in Figure 3.4, the C_t/N ratio range was 15 to 25 among the reactors, while the C_{bio}/N ratio was 2 to 3 times lower than of the C_t/N and ranged from 5 to 13. Reactor C100 had the highest Ct to C_{bio} ratio (2.85). This was most likely due to a large amount of biodegradable carbon in the digestate having already been degraded during anaerobic digestion. Related to this observation, and as expected, the initial C_t/N ratio decreased as the amount of digestate increased in the reactors. However, unlike the C_t/N ratio, the C_{bio}/N ratio increased as the amount of digestate increased up to C20 and started decreasing at C75. Interestingly, this trend is similar to those discussed in the previous sections for the RHG, ROR, and respirometry parameters.

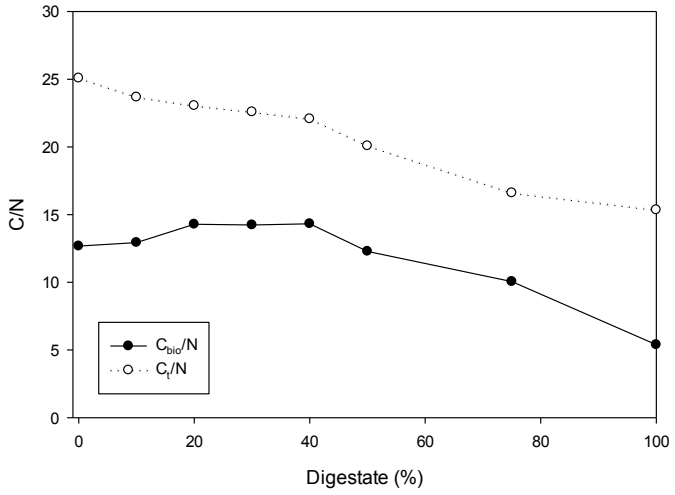

Figure 3.4. Initial C_t/N and C_{bio}/N in the reactors.

3.3.3 Total biodegradable carbon (C_{bio})

The total C_{bio} available in each reactor at start-up is presented in Figure 3.5. Observed values were those actually measured during the experiment. The calculated values were determined using the observed C_{bio} values in C0 and C100 feedstocks and the proportion of each used in each reactor. If digestate addition had no effect on the composting process; one would expect the observed and calculated values to be equal. However, observed values showed that there was more degradation in the mixtures. The highest degradation was observed in the range 20 to 40% that corresponded to the highest RHG and OM removal and the lowest maturity times.

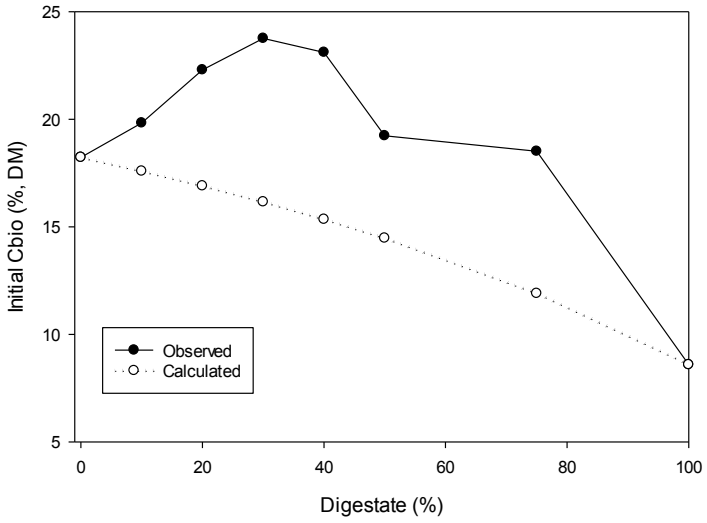

Figure 3.5. Comparison between observed and theoretical (calculated) C_{bio} at different amount of digestate.

3.3.4 Mineral forms of N (ammonia-N and nitrate-N) and their ratio

The ammonium, nitrate, and ammonium/nitrate ratio profiles during 100 days of composting in three selected reactors, C0, C40, and C100, are presented in Figure 3.6. The results of all other reactors are presented in Appendix C, Table C59 and Table C61. The initial NH_4-N content was almost six times higher in C100 compared to C0. This was expected because the digestate was obtained from the AD process, in which part of available N is already transformed to ammonia during the OM mineralization (Tambone et al., 2010). Therefore, the higher the amount of

digestate in the reactors, the higher concentration of ammonium was observed. Similar results were reported in Zeng et al. (2012) study where the digestate produced from fine fraction of residual household wastes and digested sludge had higher NH_4^+/NH_3 content compared to their fresh correspondent wastes. Based on ammonium amount attributable to C0 and C100 feedstocks, the initial ammonium concentration in C40 should have been about 2500 $mg.kg^{-1}$ DM. However, the observed value was 5065 $mg.kg^{-1}$ DM, which was about two times higher than expected. This could be caused by an imbalance in the initial C/N ratio and higher pH value in C100 compared to C40. In other words, very low C_{bio}/N ratio (≈5) and high pH in C100 triggered the release of high amounts of ammonia during the sampling before measuring the ammonium content. Even during the first week of the process, the ammonium reduction rate was much higher in C100 (from 6200 to 2750 mg kg^{-1} DM) compared to C40 (from 5065 to 4980 mg kg^{-1} DM). Nitrogen volatilization, in forms of ammonia, from the feedstocks with low C/N ratios, such as digestate, also has been reported in previous studies (Epstein, 1996; Pagans et al., 2006).

As composting proceeded, the ammonium concentration gradually decreased in all reactors. The ammonium reduction can be due to the microbial growth, volatilization, and nitrification processes. As shown in Figure 3.6, the low concentration of NO_3-N showed that significant nitrification did not start until day 65. It can be speculated that the NH_4-N loss is mostly due to cell growth and volatilization rather than nitrification. The volatilization occurs through the conversion of NH_4-N to NH_3-N, which is strongly dependent on pH and temperature where the higher values of these parameters resulted in the higher conversion rate. High temperature (over 40 °C) and pH (over 9) could probably increase the volatilization and hamper the initiation of nitrification phase in all reactors. Nevertheless, nitrification started with higher rate in C0 relative to that of the C40 and C100, which was probably due to the lower pH value in this reactor. Nitrification, detected as NO_3-N formation, usually occurs during the maturity phase and is limited by temperature above 30 °C and pH over 8 (Insam et al., 2013). In addition, high concentration of ammonia also inhibits the growth of nitrifier bacteria (de Bertoldi et al., 1983) and results in low NO_3-N concentration.

To investigate compost maturity, the ammonium and ammonium to nitrate ratio values were compared to end-point standards. Ammonium levels below 500 $mg.kg^{-1}$ DM and ammonium to

nitrate ratio below 3 were recommended as the maturity indicator according to TMECC 04.02-C and 05.02-C, respectively. In this study, all reactors have reached the maturity level by day 100 of composting based on these two indexes.

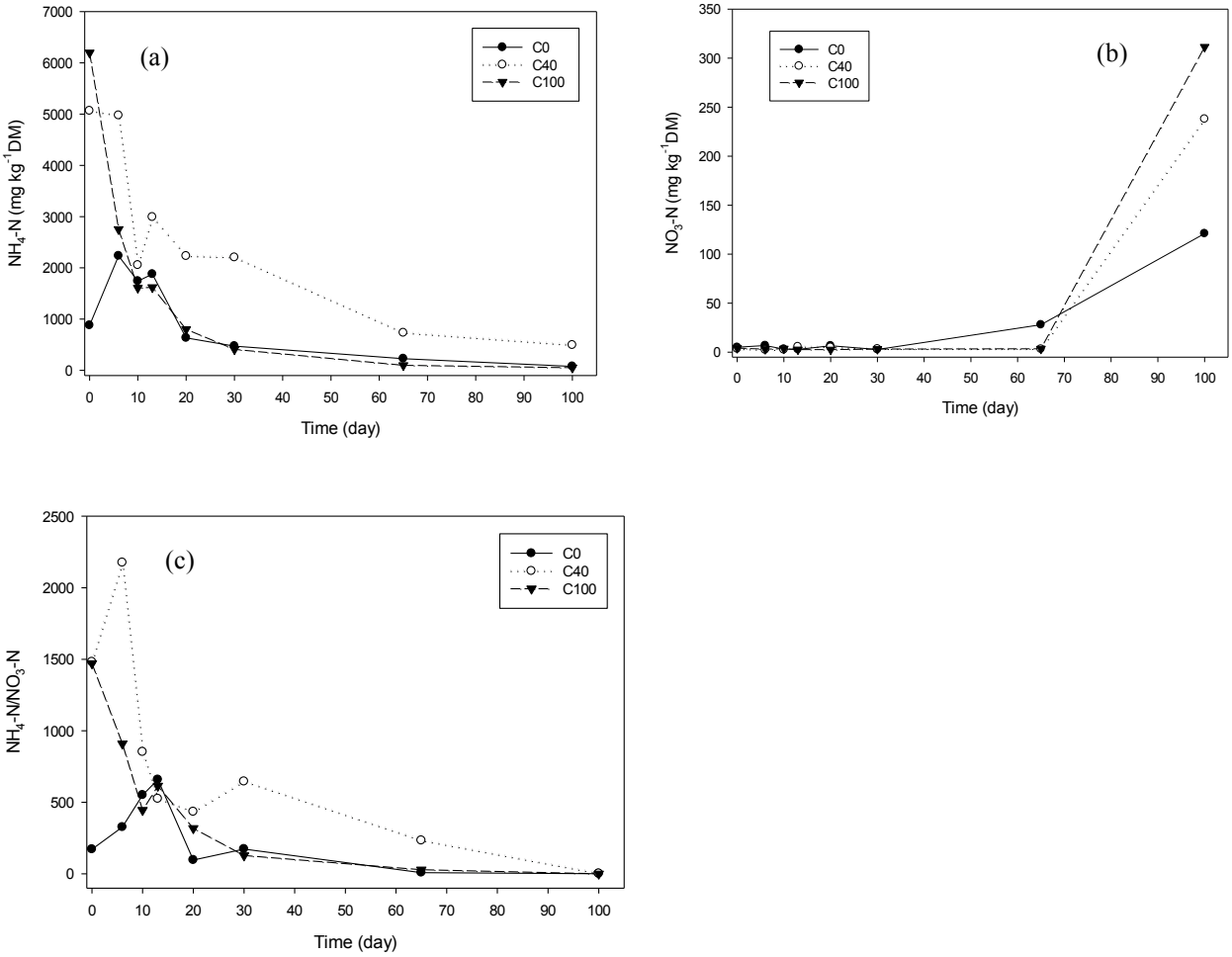

Figure 3.6. (a) NH_4-N, **(b)** NO_3-N, and **(c)** NH_4-N/NO_3-N profile during composting.

3.3.5 pH and EC

The pH and EC profiles during 100 days of composting in three selected reactors, C0, C40, and C100, are presented in Figure 3.7. The results of all other reactors are presented in Appendix C, Table C63 and Table C65. In the control reactors, C0 and C100, the initial pH values of the OFMSW and digestate were 6.1 and 8.5, respectively. The alkaline pH of the digestate can be attributed to the effect of volatile fatty acids (VFA) degradation and ammonia production during

the anaerobic digestion process. The sub-acid pH of OFMSW was probably caused by anaerobic conditions during the collection and storage of this material in the municipal solid waste system and the early stages of composting. Both conditions would lead to the formation of VFA at the beginning of the composting process (Tambone et al., 2010).

As the composting period progressed, pH increased gradually in all reactors probably due to the proteolysis and ammonification as a consequence of organic material degradation. The rapid pH increase was observed in all reactors, especially in C0, mostly during the first week of the composting process at the thermophilic phase. A higher pH change in C0 was probably due to higher ammonium production rate compared to that of the C40 and C100 (Figure 3.7). The pH increased till day 20 and then decreased in all reactors as the degradation progressed. This reduction could be attributed to the decrease in buffer capacity, such as ammonium, after day 20 in the reactors.

As shown in Figure 3.7, the EC reduced during the first 30 days in all reactors and then started to increase when the decomposition rate reduced. Throughout the composting process, mineral ions are released while organic matter is degraded (Himanen and Hänninen, 2011). In the early stage of composting when the degradation rate was high, microorganisms consumed available nutrients and this caused a reduction in EC. However, as composting proceeded, the EC started increasing while decomposition rate reduced gradually and microorganisms did not consume that much of soluble salts (Himanen and Hänninen 2011). A similar trend of EC was also observed in Cáceres et al.(2006) when monitoring composting of the solid fraction of cattle slurry. Although the EC level increased throughout the entire process, it still remained well below the maximum safe value (2500 $\mu s.cm^{-1}$) reported by Himanen et al. (2011) for the compost to be used as a final end product.

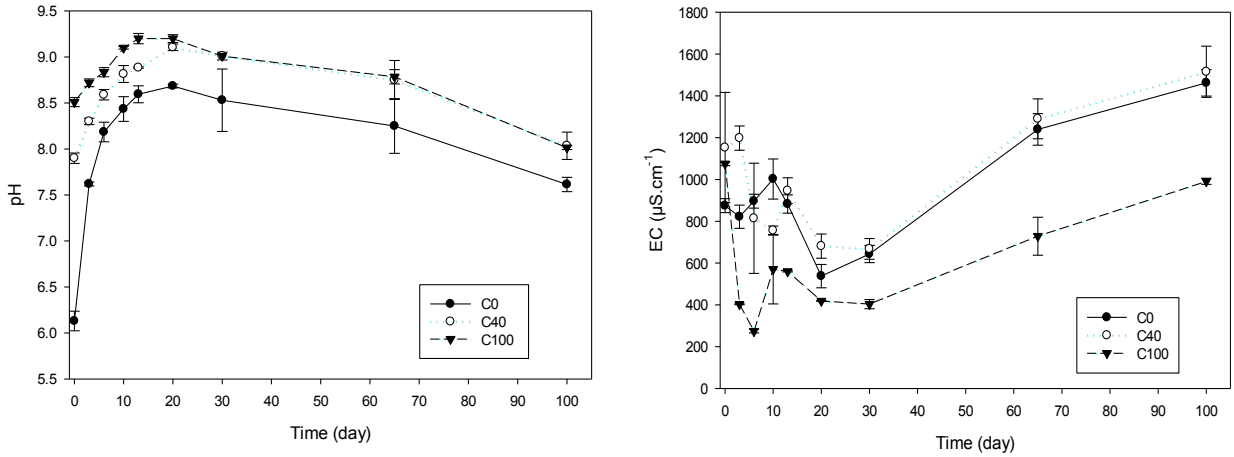

Figure 3.7. pH and electrical conductivity (EC) profile during composting.

3.3.6 Solvita®

The evolution of Solvita® indices (carbon dioxide and maturity) is shown in Table 3.5. Based on the CCQC (2001), the Solvita® carbon dioxide index can be used to monitor the stability of compost. The materials are categorized as very stable when this index is above 7. Among the reactors, C20, C30, and C40 reached the stability point of 7 in the shortest period of time (between 6 to 10 days). While in all the other reactors, it took longer (about 30 days) to be considered as very stable compost. Although the Solvita® CO_2 index indicated shorter stabilization times compared to the SOUR values in the respirometry test, there is still strong correlation (R^2=-0.87-0.96) among the results of all reactors except in C75 and C100. The lower correlation values (-0.50 and -0.71) observed in C75 and C100 can be explained by high ammonia concentrations that may have resulted in microbial inhibition, lower CO_2 generation, and consequently false stability readings. For example, the CO_2 index of 8 and NH_3-N index of 1, at day 6 in C75 and C100 showed that no or very small amount of CO_2 was generated which might be due to microbial inhibition happened at high NH_3-N content (the NH_3-N index results are not shown). The same observation was reported in Hill et al. (2013).

Compost is considered mature when the Solvita® maturity index reaches 7. In this study, as was expected based on the other examined parameters (OM, temperature, respirometry), C20, C30, and C40 required a shorter time to reach the maturity. Maturity occurred in these three reactors after 10 days, while the other reactors became mature after 30 days. Overall, Solvita®

indexes showed lower stability and maturity time compared to the respirometry test. This was expected since Solvita® measurement is a field test and not precise enough to be considered as a stand-alone measurement. However, it can be a suitable indicator of the process performance when other accurate parameters such as respirometry analysis is also used for confirmatory purposes.

Table 3.5. Evolution of Solvita® index during the composting process.

Parameter	C0	C10	C20	C30	C40	C50	C75	C100
Solvita CO_2 index								
Day 0	2	2	2	2	1	2	2	3
Day 3	4	4	4	4	4	5	5	5
Day 6	5	5	6	7	6	6	8	8
Day 10	6	6	7	7	7	6	6	6
Day 13	6	5	6	7	6	6	8	6
Day 20	6	6	7	6	7	6	6	6
Day 30	7	7	7	7	7	7	7	7
Day 65	7	7	7	7	7	7	7	7
Day 100	7	7	7	7	7	7	7	7
Solvita maturity index								
Day 0	2	2	2	2	1	1	1	1
Day 3	4	4	4	4	4	4	3	3
Day 6	5	5	6	6	5	5	4	6
Day 10	6	6	7	7	7	6	5	6
Day 13	6	5	6	7	6	6	6	6
Day 20	6	6	7	6	7	6	6	6
Day 30	7	7	7	7	7	7	7	7
Day 65	7	7	7	7	7	7	7	7
Day 100	7	7	7	7	7	7	7	7

3.3.7 A summary of key observations based on the monitored parameters

To summarize the observations, total C_{bio}, ROR, RHG, and maturity time were plotted against the digestate concentration (Figure 3.8). As shown in Figure 3.8, all parameters showed that digestate additions in the range of 20 to 40% significantly enhanced the composting process. Better performance and shorter retention times in reactors with 20-40% digestate could be attributed to both physico-chemical characteristics of the feedstock and microbial consortium (microorganisms population).

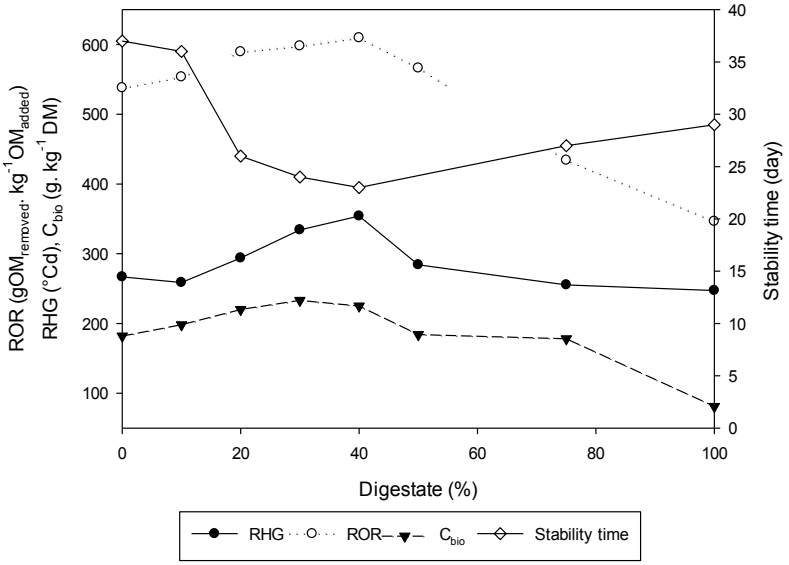

Figure 3.8. Correlation between process and maturity parameters.

To investigate inorganic nitrogen effects as one of the critical chemical parameters, the total C_{bio}, which represents carbon removal after 100 days of composting, were plotted against total ammonia nitrogen (TAN) content (Figure 3.9). TAN is the summation of un-ionized ammonia (NH_3-N) and ionized ammonia (NH_4-N). Un-ionized ammonia (UAN) or NH_3-N was calculated based on the NH_4-N concentration, pH and temperature. A 3rd polynomial function was well fitted (R^2=0.96) to the TAN-C_{bio} data. The pattern indicated that the TAN level up to 5000 mg.kg^{-1} DM could stimulate the process in terms of carbon removal. However, it seemed to become inhibitory in excess amount (above 5000 mg.kg^{-1} DM).

There are many investigations that have studied ammonia inhibition during anaerobic digestion; however, to the authors' knowledge, there are only a few studies that reported ammonia concentration as a possible reason of composting inhibition (Sánchez-Monedero et al., 2001, Fidero et al., 2013). The TAN inhibition threshold has a wide range of 2500-6000 mg.kg^{-1} DM in high solids AD systems, which varies based on the type of the reactor (continuous or batch), type of substrate, loading rates and process temperature (Poggi-Varaldo et al., 1997). However, in a comparable composting study conducted by Sánchez-Monedero et al. (2001), NH_4-N content above 7000 mg.kg^{-1} DM was reported as a possible reason for temporarily

microbial inhibition in the reactor with lower degradation rate. This value was comparable to the NH_4-N content (6900 $mg.kg^{-1}$ DM) detected in C100 with the lowest degradation rate. In addition, both respirometry and Solvita® analyses also confirmed temporary inhibition at early stages of composting in C75 and C100. As shown in Figure 3.2, C100, only fed with digestate, had lower SOUR value at day 0 compared to day 3. Observing a lower SOUR value, as an indicator of microbial activity, might be due to inhibition of the bacteria at the high ammonia nitrogen content.

Adding the digestate may have improved composting rates because it serves as a nitrogen source; however, ammonia nitrogen levels may inhibit composting if levels become too high. In this study, ammonia nitrogen appeared to improve overall performance at digestate ratios of up to 40%; however, introducing higher amounts of digestate (>40%) led to inhibition due to imbalance between ammonia nitrogen and carbon availability.

In the case of biological effects, it can be concluded that digestate inoculation within ranges 20-40% (wet weight) provides enough microorganisms that they could survive in the presence of the indigenous microorganisms and possibly enhance the process. Lower amounts of inoculum (<20%) did not have any considerable impacts on composting possibly due to insufficient sources of microorganisms. Adding excess quantities of inoculum (>40%) resulted in a reduction in OM removal in C50, C75 and C100. This could be due to the fact that substrates became the limiting factor in these reactors and inoculation did not enhance the process. All three critical parameters (RHG, ROR, and stability time) results showed that the effect of inoculation depends on the ratio of inoculum and substrate. Therefore, providing the optimum ratio is a key factor to take advantage of the inoculation in composting processes. The biological effects of digestate on the composting process will be reported in Part II which will focus on microbial populations.

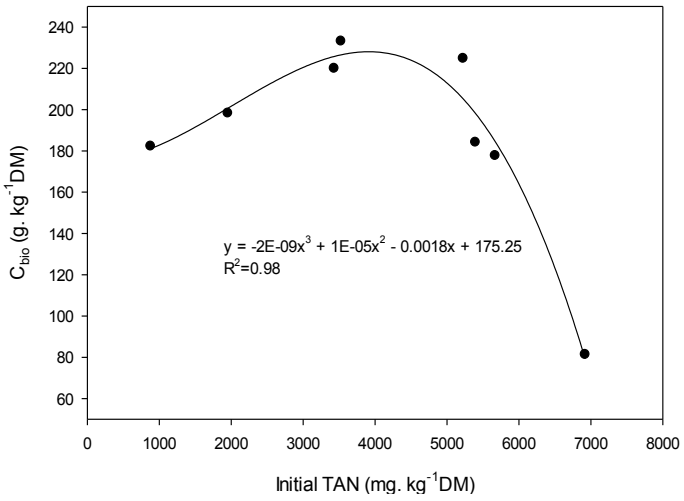

Figure 3.9. Changes of carbon removal (total C_{bio}) at varying initial TAN, fitted 3rd order polynomial function.

3.3.8 Possible benefits of OFMSW on digestate composting

Other than the positive effects that digestate can have on OFMSW during composting, OFMSW can also be considered as a physical or chemical amendment for the digestate. In this study, in the reactor fed only with digestate (C100), 15% (ww) woodchips (WC) was added to adjust the moisture content and improve the FAS of the digestate. This amount of WC filled almost half of the reactor, and consequently reduced the working volume of the reactor. In C75, the required woodchips were reduced to 7% and in C50 no wood chips were required. The results showed that OFMSW, with lower MC and higher FAS, can be considered a good candidate to improve the physical properties of digestate in terms of FAS and MC. If OFMSW is used as a bulking agent instead of WC, not only will it become stabilized during composting and increase the working volume of the reactor, but also the residuals remaining after final screening could be significantly reduced or eliminated.

Furthermore, as discussed earlier, temporarily inhibition was observed in the reactors with higher amounts of digestate (over 40%). While in the reactors with lower amounts of digestate, addition of nitrogen ammonia had no inhibitory effects and could also enhance system performance. This was probably due to availability of carbon added to the system through OFMSW. It is usually beneficial to mix nitrogen rich substrate such as digestate with substrate containing lower nitrogen. Microorganisms using lower nitrogen substrate capture ammonia

released from the digestate and use it for their synthesis. Therefore, more of the nutrients can be preserved and less ammonia is released to the atmosphere (Haug, 1993). Overall, it can be concluded that by mixing OFMSW with digestate, the C/N ratio becomes more balanced and the chance of inhibition due to high ammonia nitrogen could be reduced. Therefore, OFMSW can also be considered as a chemical amendment in digestate composting.

3.4 Conclusions

The effect of adding anaerobic digestate to the composting process was investigated. The composting experiment was conducted with different ratios of digestate to OFMSW. Digestate constituted 0, 10, 20, 30, 40, 50, 75, and 100% (wet mass) of the feedstock. The results showed that the addition of digestate to the OFMSW within the ratio of 20 to 40% enhanced the overall composting process by increasing OM removal and temperature evolution, and these reactors also reached the stability point in a shorter period of time (23 to 26 days); 30 to 36% faster than the control reactor.

TAN content introduced to the composting by the digestate could stimulate the process in terms of carbon removal. However, the results showed the concentration above 5000 $mg.kg^{-1}$ DM could be unfavourable for the biological activities due to imbalance between ammonia nitrogen and carbon availability. OFMSW was also found to be a suitable physical and chemical amendment for the digestate. It improved the physical properties of digestate in terms of FAS and MC. In addition, by mixing OFMSW with digestate, the C/N ratio becomes more balanced and the chance of inhibition due to high ammonia nitrogen could be reduced. Overall, by reducing the MRT and improving the rate of composting, the composting capacity throughput could be increased and energy requirements for aeration during the composting process will be decreased. By implementing the results achieved from this study and conducting a wide study on the operational cost of each individual reactor (with certain amounts of digestate), valuable data can be attained regarding the economic aspects. This information will assist practitioners when integrating anaerobic digestion technologies into existing composting infrastructure.

3.5 References

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CHAPTER 4: BENEFITS TO DECOMPOSITION RATES WHEN USING DIGESTATE AS COMPOST FEEDSTOCK: PART II - FOCUS ON MICROBIAL COMMUNITY DYNAMICS [3]

4.1 Introduction

Composting and anaerobic digestion (AD) are the two biological treatment technologies widely used for the stabilization of organic waste (Pognani et al. 2012). Composting is the faster technology, producing the final compost with no energy recovery, while AD has the benefits of energy recovery and reduction of greenhouse gas emissions. However, unlike finished compost, the solid-state by-product (digestate) of AD is not stabilized enough for land application. Aerobic polishing (composting) has been reported as a suitable technology for further stabilization of the digestate (Abdullahi et al. 2008; Bustamante et al. 2013).

The composting process can be enhanced by direct microbial inoculation; however, it can be more economically beneficial to use a by-product such as digestate as an inoculant instead of purchasing or preparing cultivated microbes. The literature review revealed that the co-composting of anaerobic digestate with the organic fraction of municipal solid waste (OFMSW) can bring some advantages to the composting process (Monnet 2003; De Baere 2008; Szucs et al. 2012). Since both composting and AD processes are mediated by a wide range of various microorganisms, knowledge of the behaviour, interactions and dynamics of microbial populations is necessary for a better understanding of the co-composting of the OFMSW with digestate.

[3] A version of this chapter has been submitted as: Arab, G.; Razaviarani, V,; Sheng, Z.; Liu, Y.; and McCartney, D. "Benefits to Decomposition Rates When Using Digestate as Compost Feedstock: Part II - Focus on Microbial Community Dynamics" in the *Waste Management*.

Both bacterial and fungal communities are present in a typical composting process where the activity of fungi is essential primarily in the maturation phase (Ryckeboer et al. 2003). Microbial populations may be present as active, inactive or spore forms during the composting and their activities are highly dependent on changes in the substrate's properties and physico-chemical conditions.

In a study conducted by Partanen et al. (2010), five common bacterial phyla, *Actinobacteria, Bacteroidetes, Firmicutes, Proteobacteria and Deinococcus-Thermus*, were detected in 18 different full and pilot-scale composting facilities. Interestingly, four of these phyla (*Actinobacteria*, *Bacteroidetes*, *Firmicutes* and *Proteobacteria)* are also present in the AD process (Riviere et al. 2009). The three major classes of the phylum *Firmicutes* present in compost are *Bacillales*, *Clostridia* and *Lactobacillales*. Among them *Lactobacillales,* responsible for the production of lactic acid in the early stages of composting, have also been found in AD processes (Sundberg et al. 2013; Shin et al. 2010; Franke-Whittle et al. 2014). In addition, although composting is an aerobic process, even at the optimum working conditions, the presence of anaerobes is inevitable (Ryckeboer et al. 2003). It is reported that anaerobic *Clostridia* and aerobic species of *Bacillus,* both affiliated with the phylum *Firmicutes*, are responsible for metabolizing recalcitrant materials (e.g. cellulose and lignin) in the composting process (Partanen et al. 2010). Therefore, the presence of common microorganisms in the AD and composting processes can be considered as one of the advantages of digestate inoculation in the composting process. Fungi also play a very important role, especially in the later stage of the composting process and in the degradation of materials such as lignin (de Bertoldi et al. 1983).

As compared to studies on bacterial communities, limited studies have been reported on the impact of fungi populations on the composting processes. The few reported studies however showed that fungi community is highly dependent on the substrate material and composting stages (Neher et al. 2013; Bonito et al. 2010; Ryckeboer et al. 2003).

It is well known that significant changes in microbial communities may occur due to the interactions taking place among the various populations in the composting process (Narihiro et al. 2004). Some of the bacterial communities degrade organic compounds and produce metabolites (e.g. antibiotics and enzymes) that can be detrimental or beneficial to other microorganisms. Aoshima et al. (2001) reported that lactic-acid bacteria secrete metabolites that

can be detrimental to other microorganisms in the composting process, while *Acetobacter sp.,* affiliated with the phylum *Proteobacteria,* can consume these substances for growth and possibly eliminate the harmful effects on other microbial populations (Partanen et al. 2010). Antagonistic interactions in which one species benefits at the expense of another may also take place during composting and result in changes of microbial populations. With respect to the presence of common microflora in composting and AD processes, using digestate as an inoculant during composting can alter the microbial interactions (e.g. mutualism and antagonism) and possibly enhance the process.

Aside from the benefits that may be obtained from the inoculation, the amount of inoculum is also essential to note. The quantity of inoculum introduced to the compost must be sufficient, otherwise the indigenous microorganisms in the compost do not allow the inoculum microflora to develop and effectively improve the process (Fuchs 2010). Golueke at al. (1954) reported that composting inoculation has no significant effects on the process because the inoculated microorganisms may have been outcompeted by the indigenous microorganisms. However, this study did not consider the effects of inoculum quantities during the inoculation, and thus different results could have been obtained if various amounts of inoculum had been applied.

The benefits of co-composting the OFMSW and digestate, with focus on physico-chemical parameters, were investigated in chapter 3 of this study. The objective of this chapter was to investigate the digestate benefits in terms of biological parameters, with a focus on microbial community dynamics. The bacterial and fungal diversity at different stages of composting, the correlation between microbial community structure and dynamics, and important environmental parameters were also evaluated.

4.2 Methodology

4.2.1 Material used, equipment and operation

Digestate and the organic fraction of municipal solid waste (OFMSW) were the two main feedstocks of the composting reactors. The digestate was prepared by running a high solids anaerobic digestion (HSAD) pilot-scale reactor, with the working volume of 500 L. Full details of the material types and amounts introduced to the anaerobic reactor was described in chapter 3.

The OFMSW was collected during five days from the Integrated Processing and Transfer Facility (IPTF) at the City of Edmonton (CoE). It was mostly comprised of kitchen waste, yard waste, grass, and thatch. After preparation and collection of the digestate and OFMSW, they were mixed in eight different ratios of 0, 10, 20, 30, 40, 50, 75, and 100% (digestate: feedstock, wet mass). The required amounts of water and woodchips were also added to modify the physical properties of the mixtures. To optimize the microbial performance, it is suggested to adjust the free air space (FAS) above 30% and moisture content (MC) within the range of 50-65% (Christensen 2011; Alburquerque et al. 2008). FAS measurement and calculation of required amount of woodchips was explained in Appendix C, Table C2. The composition of the material introduced to each reactor is shown in Table 4.1.

The composting experiment was operated and monitored in two phases; aeration and curing. The aeration phase was conducted in an airtight reactor with a working volume of 25 L for 30 days. The air was introduced to each reactor for two purposes; to provide the required amount of oxygen during the aerobic process and to cool down the reactor temperature, when the temperature was above 65 °C.

Table 4.1. Composition and amount of the materials in the reactors.

Reactor ID	Digestate (%, ww[1])	OFMSW (%, ww)	Digestate (kg, ww)	OFMSW (kg, ww)	Water (kg)	WC [2] (kg)	Start-up mass (kg)
C0	0	100	0	4.24	1.22	0	5.46
C10	10	90	0.44	4.00	1.04	0	5.48
C20	20	80	1.06	4.26	1.02	0	6.34
C30	30	70	1.96	4.56	1.04	0	7.56
C40	40	60	3.71	5.57	1.00	0	10.28
C50	50	50	4.62	4.62	0.50	0	9.74
C75	75	25	8.42	2.81	0.00	0.59	11.82
C100	100	0	8.87	0.00	0.00	1.57	10.44

[1] Wet weight
[2] Woodchips

The second phase (curing) was conducted for 70 days in 20 L pails with perforated ends on the bottom and top to allow natural ventilation. In both phases, the reactors were insulated with 5

cm of thick pink fiberglass and an aluminium-reflecting blanket in order to minimize heat loss. More details about the instruments used in the setup and operational factors such as aeration, temperature, and compressive loading can be found in chapter 3.

4.2.2 Microbial community analysis

4.2.2.1 Sampling and DNA extraction

The representative samples were collected at different stages of composting; the initial stage (day 0), the thermophilic phase (day 6), the after aeration phase (day 30), and the final compost (day 100). For all sampling days, the DNA was extracted from representative samples collected from all eight reactors, except day 0, in which the DNA extraction was conducted on the two main feedstocks; OFMSW (C0) and digestate (C100).

The Total genomic DNA was extracted from approximately 500 mg of well-homogenized sample using a PowerSoil® DNA isolation kit (MoBio Laboratories, Carlsbad, USA) according to the manufacturer's instructions. For each reactor, DNA was extracted from three replicate samples. A NanoDrop® 2000C spectrophotometer was used to determine the concentrations, quality and integrity of the extracted DNA. Extracted DNA samples were stored at -20 °C until submitted to the microbiology lab for the pyrosequencing analysis.

4.2.2.2 Pyrosequencing analysis

The 16S rRNA gene sequences were amplified and Illumina Miseq 16s Sequencing was performed at the Research and Testing Laboratory (Lubbock, TX, USA). Samples were amplified for sequencing in a two-step process; forward and reverse fusion primer. The forward primer was constructed with the Illumina i5 sequencing primer (TCGTCGGCAGCGTCAGATGTGTATAAGAGACAG) and the 28F primer (GAGTTTGATCNTGGCTCAG) for bacteria and ITS1F primer (CTTGGTCATTTAGAGGAAGTAA) for fungi. The reverse primer was constructed with the Illumina i7 sequencing primer (GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAG) and the 388R primer (TGCTGCCTCCCGTAGGAGT) for bacteria and ITS2R primer for fungi (CCTCCGCTTACTTATATGCTT). Amplifications were performed in 25 µl reactions with

Qiagen HotStar Taq master mix (Qiagen Inc, Valencia, California), 1µl of each 5µM primer, and 1µl of template. Reactions were performed on ABI Veriti thermocyclers (Applied Biosytems, Carlsbad, California) under the following temperature gradient: 95 °C for 5 min, then 35 cycles of 94 °C for 30 sec, 54 °C for 40 sec, 72 °C for 1 min, followed by one cycle of 72 °C for 10 min and 4 °C hold.

Amplification products were visualized with eGels (Life Technologies, Grand Island, New York). Products were then pooled equimolar and each pool was size selected in two rounds using Agencourt AMPure XP (BeckmanCoulter, Indianapolis, Indiana) in a 0.7 ratio for both rounds. Size selected pools were then quantified using the Quibit 2.0 fluorometer (Life Technologies) and loaded on an Illumina MiSeq (Illumina, Inc. San Diego, CA) 2 × 300 flow cell at 10 pM.

The nucleotide sequence reads were sorted out using a data analysis pipeline. Short sequences, noisy reads and chimeric sequences were removed through a denoising step and chimera detection, respectively. Then each sample was run through the analysis pipeline to determine the taxonomic information for each constituent read. Bacteria taxonomy was assigned using the QIIME pipeline (http://qiime.org/). Raw data, FASTA data, and data analysis methodology for fungi (http://www.researchandtesting.com/docs/Data_Analysis_Methodology.pdf) were provided by the laboratory.

Degradation of a variety of organic compounds in the composting process requires highly versatile and diverse microbial populations. The structure of the bacterial and fungal community was assessed by calculating richness, evenness, and Shannon and Simpson indexes. Richness indicates the total number of species in the community; while evenness shows the balance among the species. The Simpson index combines both evenness and richness to indicate the species diversity, and since it gives more weight to the dominant species, the influence of rare species on the index is minimal. Richness (S) was estimated from the total number of species available in the sample. Evenness was calculated using $E = {}^{H}/_{\ln S}$, where H is Shannon's diversity index and estimated using the following formula; $H = -\sum_{i=1}^{S} P_i \ln P_i$, S is the number of species and P_i is the relative abundance of each species ($P_i=n_i/N$, n_i is the peak intensity of a band and N is the

sum of all peak intensities in a lane). The Simpson index (D) was estimated using $D = 1 - \sum_{i=1}^{S} P_i^2$ (Agnolucci et al. 2013).

4.2.3 Statistical Analysis

Redundancy analysis (RDA) is a multivariate statistical analysis allows studying the relationship between two sets of variables, microbial communities (observation) and environmental variables (explanatory variables). RDA was performed using XLSTAT software version 2016 to determine the relationship between microbial communities (bacteria and fungi) and environmental factors.

4.3 Results and discussion

4.3.1 Reactors' performance

Reactor's performance of co-composting in terms of physical and chemical characteristics was investigated in Chapter 3. The results showed that the addition of digestate to the OFMSW within the ratio of 20 to 40% provided the most enhanced composting process by increasing the OM removal and relative heat generation. In addition, the respirometry results showed that the composters with 20 to 40% (%ww) digestate reached the stability point in a shorter period of time (23-26 days) compared to the other composters. The stability time for the control composter 1 was 37 days, which means a 30-36% reduction in MRT.

4.3.2 Microbial community profile and dynamics

4.3.2.1 Bacterial and fungal diversity

As shown in Table 4.2, richness, evenness and the Simpson index of the three selected reactors, C0, C40 and C100, sampled on days 6, 30 and 100 were determined to evaluate the bacterial and fungal diversity. The results of all other reactors are presented in Appendix D, Table D1. The species diversity information of the feedstocks, OFMSW (C0-D0) and digestate (C100-D0), was also presented in Table 4.2.

At day 0, the digestate (C100) had a lower richness but almost the same evenness and diversity of bacteria compared with the OFMSW (C0). Since the digestate was obtained from a partial degradation process, it contained certain types of microflora that participated in anaerobic digestion. However, the OFMSW was untreated fresh waste obtained from different sources. Therefore, it was comprised of a higher species count in both bacteria and fungi.

At day 6, the bacteria richness in C0 did not change notably while C100 showed about a 75% increase of richness relative to that of day 0. In both controls, the bacteria evenness increased with the same rate compared to day 0 and bacterial and fungal diversity reached similar index values. In C40, the bacterial and fungal diversity indexes improved compared to those of the controls' values on day 6. This could be suggesting that a wider range of microorganisms were able to benefit from the conditions in C40 at day 6 compared to those of the C0 and C100.

At day 30, as the composting process progressed, the bacteria richness in C0 and C40 enhanced by 80% and 70%, respectively relative to that of the day 6. The bacteria evenness also improved by 25% and 11% in C0 and C40, respectively, while the Simpson diversity index in both reactors was 0.94.

In C100 at day 30, the bacteria and fungi evenness and diversity index reduced considerably relative to those of day 6. It is most probable that the high concentration of ammonium in the digestate could be detrimental to some of the microbial populations and caused a temporary inhibition in C100. Lower degradation rate associated with temporary microbial inhibition was also observed in a Sánchez-Monedero (2001) study in the composting reactors with high ammonium content feedstock. The important reactor performance and biodegradation parameters (RHG, ROR and SOUR) did not changed greatly between day 30 and 100 (based on the discussion presented in Chapter 3), and therefore the bacteria diversity in C0 and C40 did not change considerably at day 100. This was expected based on trends of important physico-chemical parameters (RHG, ROR and SOUR). However, the richness, evenness and diversity index increased by 77%, 43% and 27%, respectively in C100 at day 100 relative to those of day 30. This bacterial behaviour could be due to a longer lag time and microbial adaptability in C100, which mostly contained anaerobic microorganisms. An imbalance of important parameters such as nutrients, C and N in feedstock could impact the overall bacteria diversity and consequently

hamper the microbial activities. As indicated in Chapter 3, the digestate has a lower C/N ratio and higher ammonium content compared to that of the OFMSW. A proper mixing ratio of the two substrates in C40 created the most favourable condition for species from both sources, digestate and the OFMSW, and resulted in an improvement in the bacterial diversity, based on the Simpson index shown in Table 4.2.

Table 4.2. Bacterial and fungal diversity in three selected reactors (C0, C40, and C100).

Reactor	Sampling day	Richness Bacteria/Fungi	Evenness Bacteria/Fungi	Simpson index Bacteria/Fungi
C0	0	75/26	0.43/0.34	0.71/0.59
	6	72/24	0.55/0.30	0.83/0.45
	30	130/8	0.69/0.32	0.94/0.45
	100	82/17	0.81/0.35	0.95/0.56
C40	6	79/38	0.62/0.36	0.89/0.63
	30	134/25	0.69/0.26	0.94/0.38
	100	150/11	0.76/0.46	0.96/0.54
C100	0	48/8	0.48/0.44	0.67/0.39
	6	84/31	0.54/0.30	0.83/0.43
	30	93/9	0.46/0.08	0.73/0.06
	100	161/15	0.66/0.31	0.93/0.43

This higher diversity may help to improve the reactor's performance due to interactions such as mutualism, commensalism, protocooperation and even competition in the symbiotic microbial community, which could enhance the degradation activity and make the community more tolerant to environmental changes and potentially unfavourable conditions (Allison, 2000). In other words, the reactor with a higher organic removal and shorter maturity time showed relatively higher diversity, in terms of both richness and evenness. Although it is not a perfect linear relationship, it is not hard to tell that the reactor performance and degradability rate could be associated with the higher microbial diversity.

4.3.2.2 Bacterial community dynamics

The 16S rRNA gene sequences of the bacterial population at the phylum level in three selected reactors at different stages of composting process are presented in Figure 4.1 and Table 4.3. It should be noted that the 16S rRNA gene sequences at different taxonomic levels have been quantified in all eight reactors and shown in Appendix D. However, because C40 (reactor containing 40:60 of digestate to OFMSW) showed a better performance among the reactors, according to the presented results in Chapter 3, it was selected together with two other control reactors (C0 and C100) for further microbial investigation.

As shown in Figure 4.1, the nine phyla detected during the composting were *Actinobacteria*, *Bacteroidetes*, *Firmicutes*, *Proteobacteria*, *Thermotogae, Chloroflexi, Gemmatimonadetes*, *Synergistetes* and *Deinococcus-Thermus*. However, the sequences of the first six phyla were the prevailing sequences detected in the reactors throughout composting, and therefore only they were considered in this study. Two sequences belonging to the phyla *Firmicutes* and *Proteobacteria* were the dominant bacterial communities in the fresh OFMSW (C0-D0), while *Firmicutes*, *Thermotogae,* and *Bacteroidetes* were found to be the dominant communities in the digestate (C100-D0).

As shown in Figure 4.1, the relative sequence abundance of *Firmicutes*, as the major common bacteria in both the OFMSW (C0) and the digestate (C100) were 63.6% and 31.2%, respectively. *Firmicutes* are known to produce different extracellular enzymes (e.g. cellulases, lipases, proteases) (Levén et al. 2007), and therefore the presence of this phylum reflects the ability to metabolize a variety of substrates including protein, lipids, lignin, cellulose, sugars, and amino acids in the feedstock. The prevalence of *Firmicutes* in both feedstocks (digestate and OFMSW) could be attributed to its ability to exist in both aerobic and anaerobic environments.

As composting progressed, at day 6, the sequences belonging to *Firmicutes* remained dominant in all three reactors (C0, C40, and C100), and their relative abundances increased compared to day 0. The prevalence of *Firmicutes* even at high temperatures (over 50 °C) could be attributed to their ability to sustain under thermophilic conditions (Ren et al. 2016). In all three composters, sequence reads of phylum *Firmicutes* were mostly assigned to the classes *Bacilli* and *Clostridia* (data were not shown). The *Bacillus* sp. are known to be aerobic and

thermophiles that can degrade cellulosic compounds (Mayende et al. 2006). Thus, the dominance of *Bacillus* sp. throughout the thermophilic phase of composting was anticipated. Some *Clostridium* species are well-known strict anaerobes and active in the degradation of complex hemicellulosic and cellulosic compounds (Szostak-Kotowa 2004). Therefore, it was expected that digestate was a source of *Clostridium* species. However, the tolerance to oxygen of the genus Clostridium varies and some species can survive with the presence of air or adopt to the presence of oxygen (Kawasaki et al. 2005; Marzorati et al. 2010). At day 30, the phylum *Firmicutes* almost vanished in C0 and C100, and diminished considerably by 77% in C40 compared to day 6.

The bacterial phylum *Proteobacteria* in C0 was the second dominant community at day 0 with the relative abundance of 32.6% (Figure 4.1). The dominance of *Proteobacteria* and its affiliated genus *Enterobacter* at day 0 in C0 suggested that the early fermentation and decomposition of organic compounds had already started. This could happen during the collection, transportation, and storage of this material in the municipal solid waste system. The genus *Enterobacter* are facultative anaerobes and capable of fermenting lactose under mesophilic conditions (Russo 2001). By day 6, *Proteobacteria* had decreased by 76% in C0 compared to day 0 (Figure 4.1). The reduction of *Proteobacteria* and its genus *Enterobacter* was accompanied with the dramatic rise in temperature during the early stage of the thermophilic phase, as similar observations were reported by Neher et al. (2013).

The bacterial *Thermotogae* in C100 were the second dominant communities at day 0 with the relative abundance of 55.1% (Figure 4.1). The presence and abundance of *Thermotogae* in C100 at day 0 was anticipated since this phylum exists at high temperature and is capable of degrading complex carbohydrates such as cellulose and hemicellulose, which are most of what is left after partial degradation in anaerobic digestion (Conners et al. 2006). Conversely, the relative sequence abundance of *Thermotogae* was diminished considerably, by 67%, at day 6 compared to day 0. This reduction was predictable after one-week aeration because many bacteria in the phylum *Thermotogae* are strictly anaerobic. That the family *Thermotogae* disappeared in all composters on Day 100 also confirmed this.

The presence and prevalence of phyla *Bacteroidetes* and *Chloroflexi* were ubiquitous in this study. The phylum *Bacteroidetes* and its members are found to be responsible for breaking down macromolecules such as hemicellulose, cellulose, agar and chitin in compost (Takaku et al. 2006; Wang et al. 2016). They were mostly present after the peak rise of temperature in this study, from day 30 through day 100, and the relative abundance of *Bacteroidetes* on day 30 was higher than on day 100. Tian et al. (2013) have reported a similar behaviour of *Bacteroidetes* in the composting of dairy manure and rice chaff. They observed that the phylum *Bacteroidetes* diminished significantly during the early stage of composting (day 12), but they increased at day 42.

Chloroflexi was not detected in the feedstocks (OFMSW and digestate) at day 0, however as the composting progressed the phylum *Chloroflexi* was found on day 30 and the relative abundance gradually increased in the reactors and reached the highest values at day 100. The relative abundance of *Chloroflexi* on day 30 was in the range of 5-16% and had increased by 7-23% at day 100. Similarly, Tian et al. (2013) have detected the phylum *Chloroflexi* during both the aeration (between day 13 and 42) and curing (day 122) phases of the composting process. However, the presence and abundance of *Chloroflexi* during the composting process reported in literature is varied. The abundance of the species of *Chloroflexi* has been reported in finished compost (Fracchia et al. 2006), while Danon et al. (2008) detected *Chloroflexi* only in the fresh feedstock at day 0 of composting sewage sludge and yard waste.

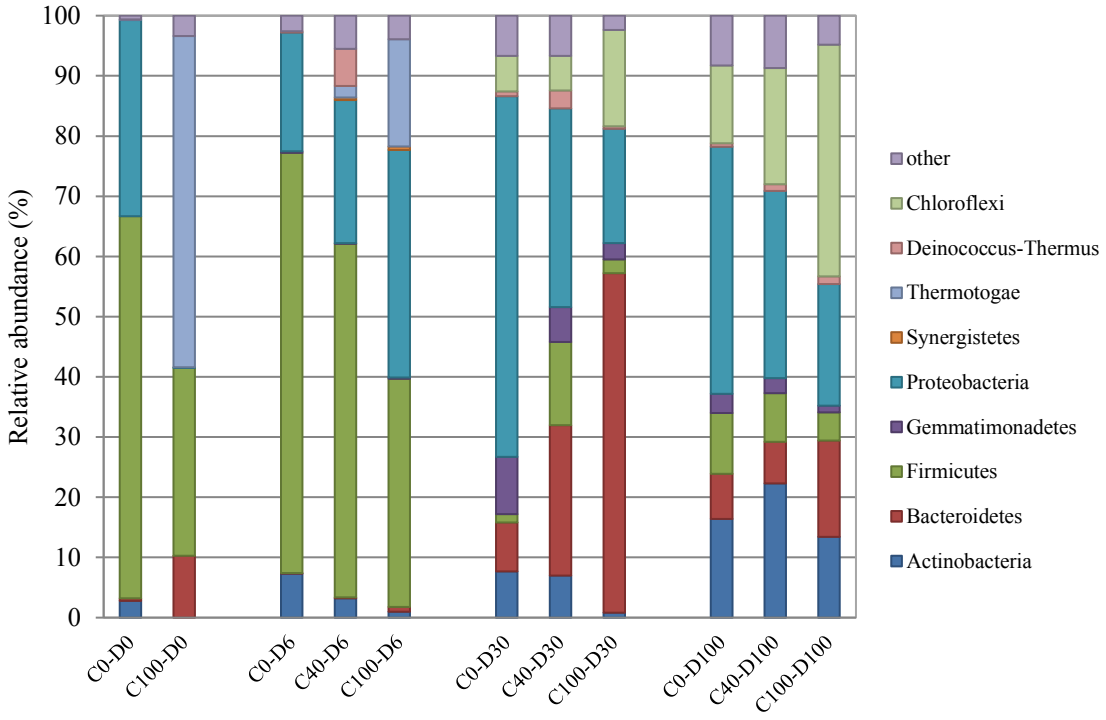

Figure 4.1. Distribution of phylum level of bacteria community in the feedstock and the three selected reactors.

Table 4.3. Abundance of phylogenetic groups of bacteria in three selected reactors during the composting.

Reactor	C0				C40			C100			
Duration (day)	0	6	30	100	6	30	100	0	6	30	100
Actinobacteria	397[a] (2.8)	1148 (7.3)	1213 (7.7)	8537 (16.4)	574 (3.2)	1824 (7.0)	18657 (22.3)	0 (0)	198 (1.0)	71 (0.8)	7027 (13.4)
Bacteroidetes	57 (0.4)	16 (0.1)	1276 (8.1)	3904 (7.5)	36 (0.2)	6513 (25.0)	5773 (6.9)	1066 (10.3)	159 (0.8)	4978 (56.5)	8391 (16.0)
Firmicutes	9006 (63.6)	10979 (69.8)	221 (1.4)	5258 (10.1)	10535 (13.8)	3595 (13.8)	6777 (8.1)	3230 (31.2)	7513 (37.9)	203 (2.3)	2465 (4.7)
Proteobacteria	4616 (32.6)	3099 (19.7)	9437 (59.9)	21343 (41.0)	4271 (33.0)	8597 (33.0)	26020 (31.1)	10 (0.1)	7493 (37.8)	1677 (19.0)	10593 (20.2)
Thermotogae	14 (0.1)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	5703 (55.1)	3529 (17.8)	18 (0.2)	0 (0.0)
Gemmatimonadetes	0 (0.0)	47 (0.3)	1497 (9.5)	1666 (3.2)	18 (5.8)	1511 (5.8)	2092 (2.5)	0 (0.0)	40 (0.2)	238 (2.7)	577 (1.1)
Synergistetes	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	72 (0.7)	119 (0.6)	0 (0.0)	0 (0.0)
Chloroflexi	0 (0.0)	0 (0.0)	929 (5.9)	6715 (12.9)	0 (0.0)	1485 (5.7)	16147 (19.3)	0 (0.0)	20 (0.1)	1412 (16.0)	20190 (38.5)
Deinococcus-Thermus	0 (0.0)	0 (0.0)	0 (0.0)	312 (0.6)	1113 (3.0)	782 (3.0)	920 (1.1)	0 (0.0)	0 (0.0)	35 (0.4)	682 (1.3)
[b]*Other*	85 (0.6)	330 (2.8)	1182 (7.5)	4321 (8.3)	987 (6.4)	1746 (6.7)	7279 (8.7)	269 (2.6)	753 (3.8)	185 (2.1)	2517 (4.8)
Totals	14161 (100)	15729 (100)	15754 (100)	52056 (100)	17947 (100)	26053 (100)	83644 (100)	10351 (100)	19824 (100)	8827 (100)	52441 (100)

[a] Number (percentage) of Sequences in Relevant Phylum.
[b] Other: *Unassigned*, *Acidobacteria, BRC1, Cyanobacteria, C. Atribacteria [OP9], Planctomycetes, Spirochaetes, C. Saccharobacteria [TM7]*.

Data analysing on Pyrosequencing results showed that there were two specific bacterial orders that might result in higher performance in C40; *Thermoactinomycetaceae*, affiliated within *Firmicutes*, and *Actinomycetales*, affiliated within *Actinobacteria.*

The bacterial orders *Thermoactinomycetaceae*, affiliated within *Firmicutes*, are capable of degrading cellulose and solubilizing lignin compounds (Martins et al. 2013). On day 6, the relative sequence abundances of *Thermoactinomyces* were 13% and 20% in C0 and C40, respectively, while no sequence of this phylum was found in C100. Considering *Thermoactinomyces* degradation function, a higher concentration of this order in C40 could be one of the possible reasons for observing higher OM removal and consequently higher RHG. As the composting progressed and reactor temperatures decreased, the relative abundance of *Thermoactinomyces* vanished by day 30 in all reactors.

Actinomycetales, branched from phylum *Actinobacteria*, are ubiquitous and considered as the indicator of composting success (Arnold 2011), and sequence abundance of this phylum represents the potential for a highly efficient and rapid composting process (Paranen et al, 2013). At day 0, no sequences of *Actinomyces* sp. were found in the digestate (C100), and its abundance was also relatively low (about 3%) in the fresh OFMSW (C0). At day 6, small growth of *Actinomyces* sp. was observed in all three composters with the highest sequence abundance in C40. At day 30, an 11% increase was observed in C40, while the relative abundance of *Actinobacteria* remained almost unchanged in C0 and C100. The increase in the phylum *Actinobacteria* after the thermophilic phase has also been observed in previous studies (Hassen et al. 2001; Chroni et al. 2009). At day 100, the relative sequence abundance of *Actinomyces* sp. increased in all reactors by 7%, 21% and 11% in C0, C40 and C100, respectively. Increasing the sequence abundance during composting is not surprising, because *Actinomyces* sp. play an important role during the curing phase, mainly in the degradation of recalcitrant compounds (Franke-Whittle et al. 2009). However, observing the higher sequence abundance of *Actinomyces* sp. in C40 during the 100 days of composting could be an indication of a better performance in the degradation of hardly degradable polysaccharides (recalcitrant) such as cellulose and lignin. In addition, *Actinomyces* sp. are fastidious microorganisms which require complex nutrients to grow, and their presence and diversity decrease significantly in too dry or wet an environment and in temperatures over 60 °C (Ryckeboer et al. 2003). Thus, their presence and abundance in C40 may suggest that more suitable conditions were provided for their growth with a proper mixture ratio of OFMSW and digestate compared to other mixture ratios.

4.3.2.3 Fungal community dynamics

The fungal 16S rRNA gene sequences and the percentage of major phylotypes in three selected reactors at different stages of the composting process are presented in Figure 4.2 and Table 4.4. The results of all other reactors are presented in Appendix D. As shown in Table 4.4, throughout the experiment, eleven fungal genus sequences were identified in the fungal sequence reads; ten genera belong to phylum *Ascomycota* and one genus belongs to *Zygomycota*. On day 0, the greatest relative sequence abundance of fungi in both feedstocks belonged to the order *Saccharomycetales*, affiliated within the phylum *Ascomycota.* The genera *Galactomyces* and

Pichia, branched from *Saccharomycetales*, were the two predominated genera in the feedstocks where the first genus accounted for 77% of sequence reads in the digestate (C100) and the first and latter accounted for 40% and 37%, respectively in OFMSW (C0) (Figure 4.2). This could have arisen from the wood-based feedstock used in our study, since the large portion of the feedstock was comprised of yard waste. The dominance of *Saccharomycetales* has also been reported in previous studies that used the grass and yard waste as composting feedstocks (Covino et al. 2016; Bonito et al. 2010). On day 6 of the composting, as shown in Figure 4.2, the two genera *Thermomyces* and *Scytaldium* became predominant fungal communities in C0 and C100, respectively. The genus *Thermomyces* are thermophilic moderate growth rate fungi while the genus *Scytaldium* grow fast during the thermophilic phase and both degrade cellulosic compounds (Straatsma et al. 1994). This fungal proliferation could be partly due to the types of substrates being composted in these two reactors, as in C0 the fresh organic waste was decomposed while C100 contained partially degraded organic materials with a large amount of recalcitrant compounds remaining. The propagation of fungal sequences in C40 was more diverse at day 6, suggesting that the recipe of a 40:60 ratio of the digestate and OFMSW could provide better nutrients appropriate for various fungal genera. This postulate can be reinforced since the total sequence abundance of fungi in C40 was considerably higher than those of C0 and C100 at day 6, shown in Table 4.2. All four major sequence abundances of *Dipodascus* (17%), *Galactomyces* (37%), *Pichia* (17%), *Saccharomyces* (24%) in C40 belonged to the order *Saccharomycetales* involved in the fermentation of various carbohydrates(Ryckeboer et al. 2003). Nakasaki et al. (2013) investigated the effects of adding *Pichia* as an inoculum during composting. It was observed that *Pichia* can increase the organic matter degradation and eliminate the initial lag phase of the process. Interestingly, C40 had the highest concentration of *Pichia* among the reactors. The other dominant genus in C40 was *Galactomyces,* which was also used as an inoculum to accelerate the degradation of organic matter in pig slurry (Zhou et al. 2013). Neher et al. (2013) also mentioned that *Galactomyces* produce cellulolytic enzymes, which improve the organic matter degradation during composting.

As composting progressed and temperature decreased (about 40 °C) at day 30, the genus *Scytaldium* constituted the dominant percentage (97%) of the total fungal sequences in C100 while the two genera *Thermomyces* (33%) and *Scytaldium* (66%) were the prevailing sequences in C0 (Figure 4.2). In C40, all the four major genera vanished and the sequences were replaced

with the genera *Scytaldium* (78%), *Thermomyces* (4%) and *Trichocoma* (5%). The total number of fungal sequences in all three reactors decreased compared to those on day 6. This alteration could have arisen from the changes in substrate characteristics and temperature peaks. It is well-documented that a low nutrient nitrogen level is a rate limiting factor for the activities of the cellulose degrading fungi while a low level of nutrient nitrogen is often essential for the lignin degrading fungi (Dix and Webster 1995). On day 100, the two thermophilic genera, *Trichocoma* (36%) and *Scytaldium* (55%) were dominant in C0, while in C100 the genus *Mortierella,* affiliated within the phylum *Zygomycota*, was found to be dominant with a relative abundance of 74% (Figure 4.2). The relative distribution of fungal genera in C40, unlike those in the control reactors, was accompanied with the appearance and prevalence of the mesophilic genera *Chaetomium* (64%) and *Acremonium* (21%). In contrast, the relative abundance of *Scytaldium* reduced considerably from 78% on day 30 to 6% on day 100. Both *Chaetomium* and *Acremonium* are the two common fungal genera that participate in lignin degradation by secreting xylanase (Longoni et al. 2012). In addition to the degradation effects of these two genera during composting, Sivapalan and Morgan (1994) found that the inoculation of final compost with *Chaetomium* and *Acremonium* can also enhance the growth of tomato plants. Therefore, the appearance and abundance of these two genera at the final stage of composting can be considered as a sign of a better final product. It has been observed that *Chaetomium* are noticeably stimulated by nitrogen sources (Domsch et al. 1980), and therefore the prevalence of *Chaetomium* in C40 could be due to the availability of TAN (as a nitrogen source) with over 5-fold higher concentration compared to those of the control reactors (C0 and C100).

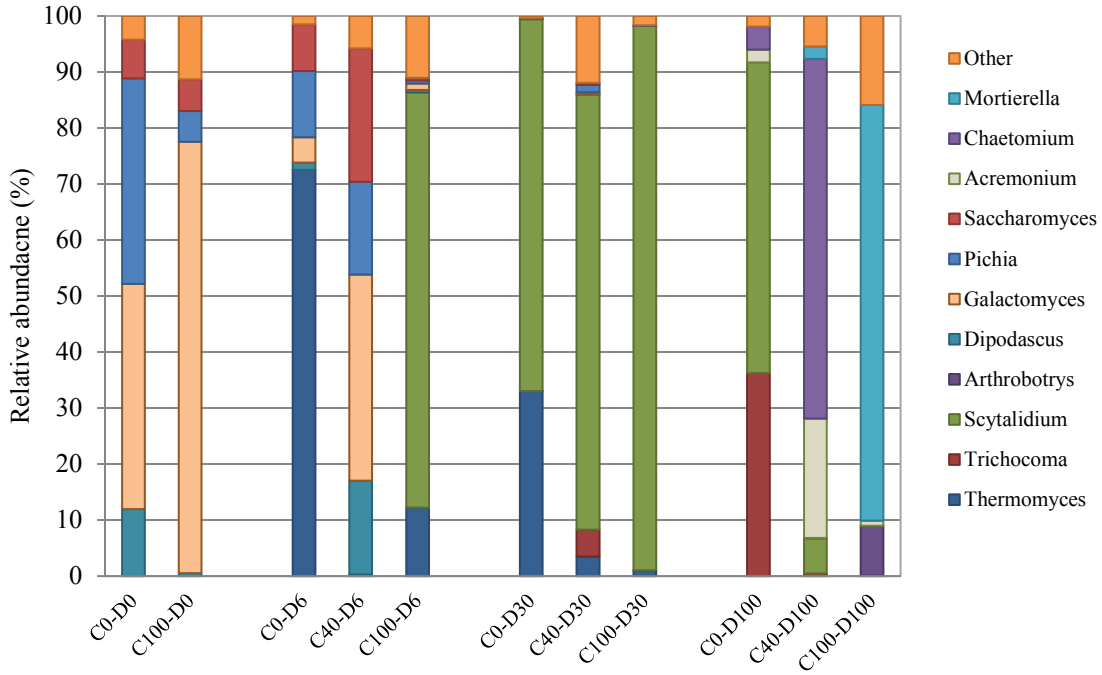

Figure 4.2. Distribution of genus level of fungi community in the feedstock and three selected reactors.

Table 4.4. Abundance of phylogenetic groups of fungi in three selected reactors during the composting.

Reactor	C0				C40			C100			
Duration (day)	0	6	30	100	6	30	100	0	6	30	100
Thermomyces	3 (0) [a]	22332 (73)	5272 (33)	0 (0)	282 (0)	1166 (4)	0 (0)	0 (0)	2037 (12)	135 (1)	0 (0)
Trichocoma	0 (0)	0 (0)	1 (0)	23066 (36)	0 (0)	1586 (5)	300 (0)	0 (0)	0 (0)	5 (0)	51 (0)
Scytalidium	0 (0)	1 (0)	10582 (66)	35307 (55)	0 (0)	25779 (78)	4003 (6)	0 (0)	12324 (74)	12751 (97)	3 (0)
Arthrobotrys	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	33 (0)	0 (0)	0 (0)	0 (0)	4688 (9)
Dipodascus	4506 (12)	408 (1)	7 (0)	0 (0)	14420 (17)	24 (0)	0 (0)	281 (1)	75 (0)	1 (0)	0 (0)
Galactomyces	15175 (40)	1382 (4)	7 (0)	0 (0)	31799 (37)	97 (0)	0 (0)	39301 (77)	191 (1)	5 (0)	0 (0)
Pichia	13837 (37)	3637 (12)	7 (0)	0 (0)	14281 (17)	440 (1)	0 (0)	2804 (5)	98 (1)	7 (0)	0 (0)
Candida	2622 (7)	2568 (8)	6 (0)	0 (0)	20590 (24)	121 (0)	0 (0)	2897 (6)	76 (0)	0 (0)	0 (0)
Chaetomium	0 (0)	0 (0)	0 (0)	1464 (2)	0 (0)	0 (0)	13519 (21)	0 (0)	0 (0)	0 (0)	473 (1)
Acremonium	0 (0)	0 (0)	0 (0)	2629 (4)	0 (0)	0 (0)	40768 (64)	0 (0)	0 (0)	0 (0)	0 (0)
Mortierella	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1396 (2)	0 (0)	0 (0)	0 (0)	39008 (74)
[b] *Other*	1585 (4)	462 (2)	65 (0)	1194 (2)	4972 (6)	3957 (12)	3450 (5)	5761 (11)	1831 (11)	217 (2)	8348 (16)
Totals	37728 (100)	30790 (100)	15947 (100)	63660 (100)	86344 (100)	33170 (100)	63469 (100)	51044 (100)	16632 (100)	13121 (100)	52571 (100)

[a] Number (percentage) of Sequences in Relevant Genus.
[b] Other: *Unassigned*, *Xeromyces,Emericella, Penicillium, Deborymeces, Cephalosporium, Trichthecium, Mrakiella, and Trichosporon*.

4.3.3 Correlation between bacterial-fungal communities and environmental variables

Redundancy analysis (RDA) was applied using XLSTAT software to determine the correlation between bacterial and fungal sequence reads and environmental variables (temperature, OM, C/N ratio, TAN and NO_3-N) during the experiment. This statistical analysis helps to determine the most influential factors and choose the level of influence of various environmental variables affected the microbial species variation. Two separate biplots (a and b)

of the RDA results are shown in Figure 4.3. In the bacterial RDA plot (Figure 4.3a), the combined two axes explained 54.68% of the bacterial variations with significant correlations ($p < 0.05$) between environmental variables and bacterial populations. For the fungal genera (Figure 4.3b), the combined two axes significantly ($p < 0.05$) explained 69.16% of the variation between environmental factors and fungal populations. This indicates that the factors included here for both bacteria and fungi are the major factors shaping the microbial communities. Forward selection, a stepwise linear regression to choose a subset of explanatory variables for the final model, was used to determine the most influential gradients, which have been the drivers of the bacterial and fungal composition changes during the composting. The explanatory variable (environmental variable), which was unsuccessful in significantly ($p < 0.05$) improving the model's explanatory power, was not considered. Through this procedure, TAN ($p = 0.002$), NO_3-N ($p = 0.010$), and temperature ($p = 0.018$) were found to statistically explain the variation ($p < 0.05$) in the distribution of the bacterial genera. For the fungal sequences, the temporal variation was also best explained by TAN ($p = 0.026$), NO_3-N ($p = 0.004$), and temperature ($p = 0.04$). pH and EC did not statistically explain the variation ($p > 0.05$) either in the distribution of the bacterial or in the fungal genera, thus we were unable to know exactly how much these parameters contributed to the variation through statistical analysis. Variation partitioning analysis, a method that explains the individual effects of the most significant parameters on the variation of microbial community composition without the effects of others (Borcard et al. 1992), was performed to extract the variation of bacterial and fungal composition explained solely by the three significant variables NO_3-N, TAN and temperature. The variation of bacterial composition was explained by temperature 26.0% ($p <0.0001$), TAN 23.8% ($p = 0.002$), and NO_3-N 22.4% ($p <0.0001$). The variation shared by NO_3-N, TAN and temperature was 52.0% ($p <0.0001$). Temperature solely explained 21.15% ($p = 0.041$) of the variation of fungal composition, while TAN and NO_3-N explained 29.76% ($p = 0.012$) and 32.07% ($p = 0.008$), respectively. The shared variation was 67.82% ($p = 0.004$).

Although NO_3-N, TAN and temperature were the primary environmental parameters governing the bacterial composition, it does not imply that other environmental factors have no effect on bacterial composition. However, for the fungal genera, OM and C/N ratio failed to significantly ($p > 0.05$) explain the variation and therefore were removed from the model. Two separate RDA biplots were performed to assess the different levels of influence of environmental

parameters on the bacterial and fungal structures (Figure 4.3 and Figure 4.4). The positions of the sampling days, indicated as the age of the compost at different sampling times, were shown in the biplots. An acute angle between the two environmental parameters indicates a strong (positive) correlation and an obtuse angle shows a weak (negative) correlation.

As shown in Figure 4.3, the genera B8 and B12 had positive correlations with TAN and existed only at day 0, suggesting that these genera were able to exist with high TAN and as composting progressed they vanished completely. It should be noted that as composting progressed, NH_4-N could be consumed through the ammonium oxidization to nitrate and/or lost as free ammonia at high temperature and pH. In this study, the possibility of nitrogen loss due to the high temperature and pH values is more acceptable. The main factor affecting B9, B10 and B11 was temperature, as these genera were found only at day 6 and survived at the thermophilic phase. The abundance of these three genera could be enhanced in the thermophilic stage by controlling two other relevant environmental parameters, C/N ratio and OM, as these genera showed positive correlations with these two factors. The importance of temperature's role in the microbial activities and community dynamics has been reported in Xiao et al.(2009) and the effects of temperature and substrate availability on the microbial population have also been highlighted by Cahyani et al. (2003). As shown in Figure 4.3, the sequence B17, affiliated within *Thermotogae*, existed only at the thermophilic phase and had a positive correlation with TAN, suggesting that this genus could grow at a high level of ammonium concentration. The factors affecting genera B1, B2, B4, B5, B6, B7, B15 and B16 imply that these bacteria were better adapted and fairly tolerant of low temperatures and low TAN environments. In addition, these genera were able to grow and exist at the low level of substrate availability, as they were in abundance when the OM and C/N ratio decreased at day 100. The genus B13 existed persistently in all reactors and at different sampling times except day 0, suggesting that this genus was able to exist at different environmental conditions and as composting progressed its abundance improved. However, this genus had a negative correlation with TAN, suggesting that the growth of B13 relies on an environment with low TAN concentration.

As shown in Figure 4.4, the genus F1, affiliated within *Ascomycota*, existed only at the thermophilic phase and found at day 6, suggesting that this genus could grow in a high temperature environment. Genera F4, F9, F10, and F11 appeared during the last days of

composting which suggests that these genera were able to exist at low temperature and with low levels of TAN. The factor affecting genera F5, F6, F7, and F8 suggests that these fungi were fairly tolerant in a high TAN environment and as they showed a positive correlation with TAN, they are able to grow at a high level of ammonium. As shown in Figure 4.4, the majority of the fungal genus were found during the initial stage (day 0) and late stage (day 100) of composting. This fungal proliferation in composting is expected because during the first stage, fungi rapidly degrade carbon sources resulting in a pH drop where the fungal sequences increased. Within a few hours of composting, ammonification occurs and causes a pH increase favourable for bacteria that can outcompete fungi. At the late stage as substrates decrease, thermophilic activities cease and temperature declines when fungi reappear to degrade the remaining complex polymers such as cellulose, hemicellulose and lignin.

Microbial communities are affected by environmental factors and altering the environmental factors could be considered key to enhancing the composting performance. Inoculation during composting is a strategy to improve the abundance and diversity of uncultured bacteria and fungi through the control of relevant environmental parameters. For example, in this study, TAN was one of the primary factors affecting bacterial composition. Therefore, alterations of bacterial diversity in response to TAN could be carefully monitored to provide the optimum TAN required to prepare the best bacterial diversity for composting. Bacterial diversity could then be enhanced through the addition of digestate, as a source of TAN, in a proper ratio to the OFMSW. Genera B1, B2, B4, B5, B6, B7, B15 and B16 appeared at a later stage and had strong correlation with nitrate and ammonium. This may suggest that the prevalence and abundance of these genera relies on an environment with low TAN and high NO_3-N concentrations. The abundance of these genera could be enhanced by controlling these environmental factors in compost.

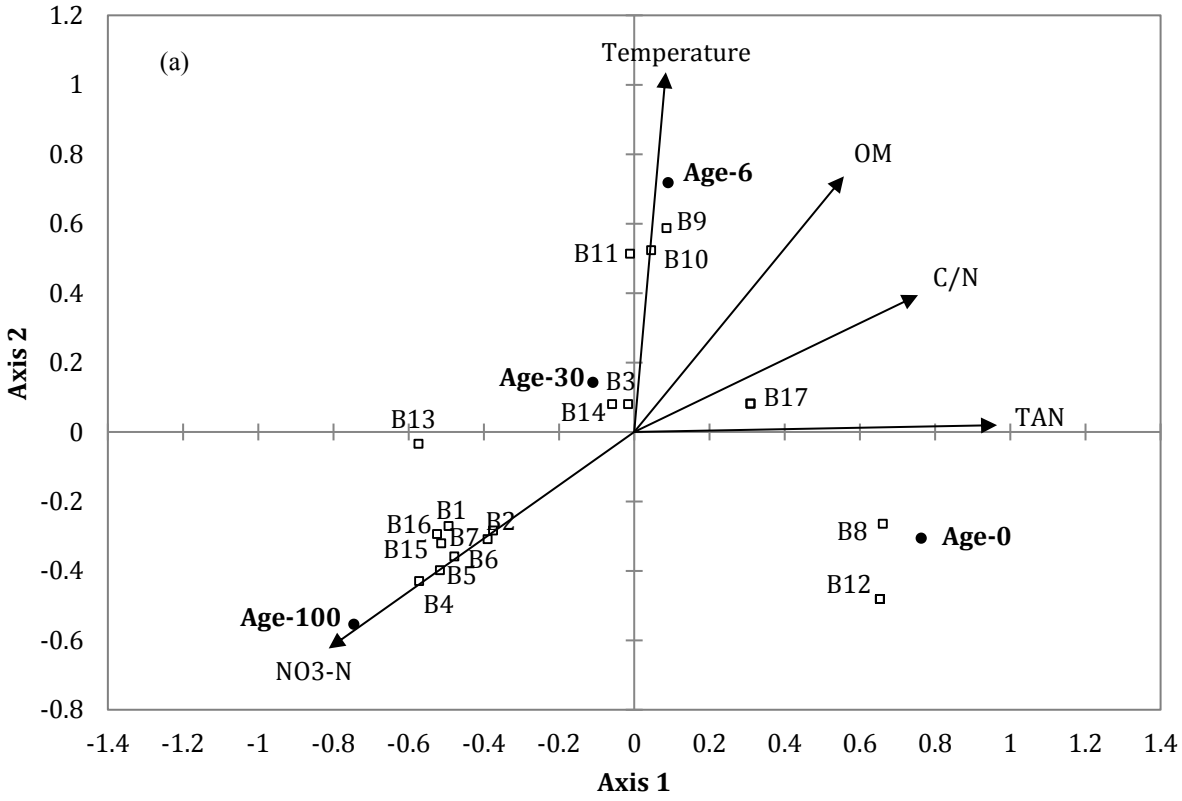

Figure 4.3. Redundancy analysis (RDA) biplot showing the correlation between the sequence abundance of bacterial communities and the environmental variables [Temperature, organic matter (OM), C/N ratio, total ammonia nitrogen (TAN), and NO_3-N]. The environmental variables represented in the RDA are shown as vectors in the plot. The black dots represent the age of the compost/sampling days (0, 6, 30 and 100). The square symbol represents the sequence genus of bacterial communities that include: B1: *Actinomyces*; B2: *Nocardiopsis*; B3: *Marinilabilia*; B4: *Cytophaga*; B5: *unknown (Chloroflexi, family SHA-31)*; B6: *unknown (Chloroflexi, order CFD-26)*; B7: *unknown (Chloroflexi, family-A4b)*; B8: *Lactobacillus*; B9: *Bacillus*; B10: *Planococcus*; B11: *Planifilum*; B12: *Proteus*; B13: *Pseudomonas*; B14: *Sphingomonas*; B15: *Steroidobacter*; B16: *Devosia*; B17: *Thermotogae*.

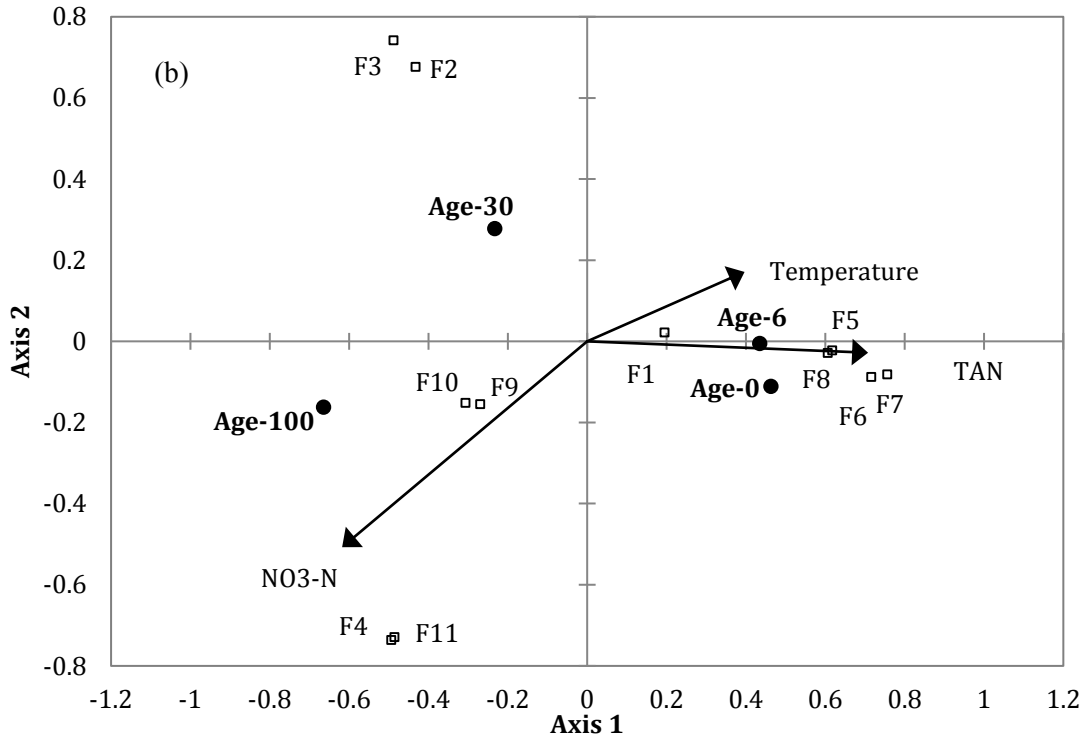

Figure 4.4. Redundancy analysis (RDA) biplot showing the correlation between the sequence abundance of fungal communities and the environmental variables [total ammonia nitrogen (TAN), NO_3-N and temperature]. The environmental variables represented in the RDA are shown as vectors in the plot. The black dots represent the age of the compost/sampling days (0, 6, 30 and 100). The square symbol represents the sequence genus of bacterial communities that include: F1: *Thermomyces* sp.; F2: *Talaromyces*; F3: *Scytaldium*; F4: *Arthrobotrys*; F5: *Dipodascus* F6: *Galactomyces*; F7: *Pichia*; F8: *Saccharomyces*; F9: *Acremonium*; F11: *Chaetomium*; F11: *Mortierella*.

4.4 Conclusions

Better composting performance, in terms of OM degradation and stability time, was associated with higher microbial diversity, based on the Simpson index. A proper mixing ratio of the two substrates in C40 probably created the most favourable condition for species from both of the sources, digestate and the OFMSW. There were two specific bacterial orders that might result in higher performance in C40; *Thermoactinomycetaceae*, affiliated within *Firmicutes and Actinomycetales*, affiliated within *Actinobacteria.* The highest concentration of bacterial order *Thermoactinomycetaceae*, which is capable of degrading cellulose and solubilizing lignin

compounds, was observed at day 6 in C40. In addition, observing the higher sequence abundance of *Actinomyces* sp. in C40 during the 100 days of composting could be an indication of a better performance in the degradation of hardly degradable polysaccharides such as cellulose and lignin.

At the early stage of composting, *Galactomyces* and *Pichia*, the two fungal communities used as inoculum in composting processes were found to have a higher abundance in C40. While, at the final stage of composting, *Chaetomium* and *Acremonium* were the two abundant genera which probably resulted in higher OM degradation by secreting xylanase and participating in lignin degradation.

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CHAPTER 5: EFFECTS OF DIGESTATE CO-COMPOSTING ON CURING PHASE OF COMPOSTING [4]

5.1 Introduction

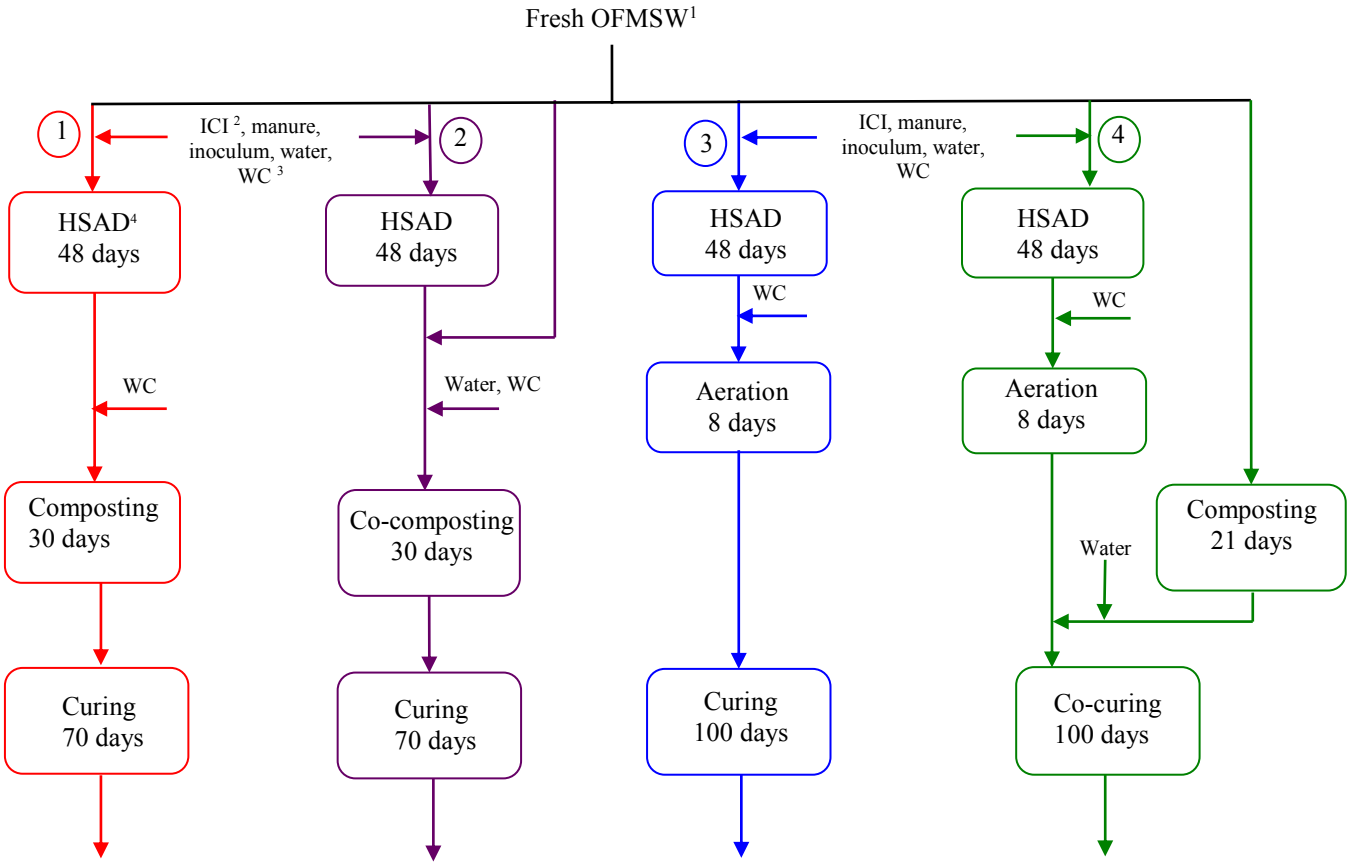
Anaerobic digestion (AD) is considered one of the most suitable technologies in organic waste treatment. However, the management of digestate, the solid residues generated during organic matter degradation, is one of the challenges that AD plants currently encounter. Composting is a promising method to improve the digestate quality and assure the maturity and stability of this by-product. Digestate can be composted as a sole feedstock or co-composted with other organics and considered as an inoculum or amendment in composting processes. As an amendment, digestate can enhance the physical and/or chemical properties of compost feedstock by providing moisture content and nutrients such as nitrogen and phosphorus for compost feedstock. Digestate can also improve the biological properties of the compost. Digestate inoculation can enhance the amount and diversity of microbial populations and possibly improve the overall performance of composting. However, when to introduce the inoculant during composting is not well understood. Xi et al. (2005) studied the microbial kinetics during compost inoculation and demonstrated that microbial concentration is a main limiting factor at the first stage (degradation phase) while the substrate concentration is the key limiting factor at the second stage (maturity phase). According to this study, inoculation during the first stage seems to be more effective in order to speed up the composting process. However, some authors (Huang et al. 2009, Zeng et al. 2010) suggested that inoculation during the second phase (curing phase) could accelerate the overall composting process more effectively. These different findings are not surprising because of the complexity of microbial reactions in compost and the lack of understanding of all the interactions, mechanisms and processes that lead to the end results.

[4] A version of this chapter has been submitted as: Arab, G. and McCartney, D. "Effects of digestate co-composting on curing phase of composting" in the *Waste Management*.

In order to benefit from digestate co-composting, the quantity and the stage of composting (aeration phase and curing phase) in which digestate is added is critical. If both the quantity and time of inoculation can be controlled appropriately, digestate co-composting may help to speed up the overall composting process.

The City of Edmonton (COE) is integrating a new high solids anaerobic digestion (HSAD) facility into their existing composting infrastructure. Four different options are available to treat the digestate within the facilities. Digestate can be (1) composted and cured separately, (2) co-composted (mix with fresh OFMSW) and cured, (3) aerated and cured separately, and (4) aerated separately and co-cured (mixed with 21-day composted OFMSW). The material flow for these four options is shown in Figure 5.1. Options 1 and 2 were investigated in Chapter 3. The results showed that both digestate and OFMSW could benefit from each other during co-composting. OFMSW could increase the physical properties (air space and moisture content) of the digestate, provide a more balanced C:N ratio for the microorganisms, and reduce the chance of inhibition occurring due to a high total ammonia nitrogen (TAN). On the other hand, TAN available in the digestate could also stimulate carbon removal and increase composting rates. A limit of 5000 $mg.kg^{-1}$ DM TAN was reported; however, some inhibition was observed at higher levels. Overall, higher organic matter removal and temperature evolution was observed in the reactors with 20-40% (%ww) digestate. Also, the stability time in these reactors was reduced by 30-36% compared to the controls. As discussed in Chapter 3, the results showed that digestate addition at the initial stage of composting (aeration phase) could improve the overall performance during composting.

The purpose of this study was to evaluate the effects of adding polished digestate to the curing phase, which are the options 3 and 4 at the COE full-scale facility. By comparing the results to the previously studied scenarios (option 1 and 2), the most suitable option for digestate post treatment will be suggested.



[1] Organic fraction of municipal solid waste.
[2] ICI: institutional, commercial and industrial organic waste, SSO: source separated organics.
[3] Woodchips, [4] high solid anaerobic digestion.

Figure 5.1. Material flow showing four possible integration scenarios for the anaerobic digestion facility at CoE.

5.2 Materials and methods

5.2.1 Equipment and operation

The HSAD was a pilot-scale (500L) reactor previously detailed in Chapter 3. This was scaled down based on BIOFerm technology (BIOFerm Energy Systems, Viessmann Group).

Aerobic polishing was conducted in the HSAD reactor with the introduction of an air distribution header on the floor of the vessel and the use of a compression device to simulate

full-scale material weight. The digestate was aerated for eight days as per normal operation of some HSAD processes.

The curing phase was conducted in 25L reactors previously described in Chapter 3. Each reactor was insulated with 5 cm of thick pink fiberglass and an aluminium-reflecting blanket to minimize heat loss. The insulated reactors were then placed in a temperature-controlled chamber. During the experiment, the chamber temperature was adjusted to 40°C. This simulates the temperature that would be at the core of the curing piles in the full-scale operation. Compressive loads were applied to each reactor to simulate the compressive settling that exists in the full-scale curing piles. The weight used varied in each reactor and was calculated based on the bulk density of the substrate in each of the composters. The simulated height was 1.5 m, which is the middle height of the curing piles in the Edmonton full-scale facility. Air was supplied to each reactor to ensure that oxygen was not the limiting reactant and to cool down the inside of the reactors, if the temperature was higher than 65°C. The air was supplied using an aluminum tank air compressor (1.0 HP, 1.6 Gal, 1610A). The input air was pre-conditioned by passing through a humidifier. Turning frequency was once every 20-25 days. At each turning day, each reactor's material was thoroughly mixed after unloading and the representative samples were obtained by mixing sub-samples taken from different points (top, bottom, middle and corners) of the bulk material.

5.2.2 Feedstock

The anaerobic digester feedstock recipe was prepared to align with the expected full-scale feedstock to be used by the City of Edmonton (CoE). Two consecutive HSAD batches were processed to prepare the digestate. The first batch generated digestate inoculum for the second HSAD feedstock batch. In the second batch, about 45% (wet mass) of the digestate inoculum prepared in the first batch was mixed with fresh feedstock.

The three main feedstock components used in the AD process were (1) pre-treated organic fraction of municipal solid waste (OFMSW) with the particle size of <3" collected from the Integrated Processing and Transfer Facility (IPTF) in CoE; (2) source separated organics (SSO) collected from institutional, commercial and industrial (ICI) sectors; and (3) horse manure

collected from one load of manure delivered by a stable to the IPTF (mixture of horse manure, urine, and sawdust). The inoculum and amendments used in batch 1 were composed of a mixture of beef feedlot manure, construction wood waste chips (from the CoE), and wheat straw. The digestate produced in batch 1 was used as the inoculum in batch 2. Water was also added to adjust the total solids of the digester in the range of 30-35%. The composition and amount of the materials used in each batch of the dry digester are listed in Table 5.1.

Table 5.1. Composition and amount of the materials in the anaerobic digestion batches.

	Batch 1	Batch 2	Batch 1	Batch 2
Material	% (wet weight basis)		kg (wet weight basis)	
OFMSW (<3")	46.8	26.5	146.0	101.2
ICI SSO waste	42.1	23.9	131.5	91.2
Horse manure	0.9	0.5	2.9	2.0
Inoculum [a]	4.2	45.3	13.2	173.2
Wood chips	3.8	2.6	11.8	10
Water	2.1	1.2	6.6	4.6

Note: [a] Batch 1 consisted of beef feedlot manure and wheat straw and batch 2 consisted of digestate prepared in the first batch.

After the digestate was prepared in the HSAD reactor, it was mixed with the green wood chips and polished during eight days of aeration. The required amount of wood chips was calculated based on the free air space measurements.

Polished digestate and composted OFMSW were the two main feedstocks of the curing reactors. The representative polished digestate sample required for the composting was prepared by thoroughly mixing the digestate and using the quartering method (ASTM C 702-98). Composted OFMSW samples were collected over a five-day period from the curing process feedstock at the CoE full-scale facility. The curing feedstock was the semi-stabilized product from the Edmonton Composting Facility (ECF). The ECF feedstock was the OFMSW aerated for about three weeks in agitated bed basin style composting methods manufactured by Sorraine. After aeration in the ECF, the product was screened and particles passing through the 0.95 cm (3/8 inches) openings became feedstock for the curing process.

Both composted OFMSW and the polished digestate were analysed for physicochemical characteristics. To compare variations between two feedstocks, a two tailed *t*-test was applied for

each dependent parameter presented in Table 5.2. A *p*-value below 0.05 was considered statistically significant.

Table 5.2. Characterization of co-composting reactor feedstocks: OFMSW and digestate.

Parameter	Composted OFMSW	Polished digestate	n[2]	*p*-value
Bulk density (kg. m^{-3})	373±27 [1]	299±15	3	<0.01
Total solids (%)	63±2	48±4	3	<0.01
Volatile solids (%DM)	63±3	51±3	3	<0.01
pH	6.8±0.2	8.3±0.0	3	<0.01
EC (µS. cm^{-1})	2513±60	1134±68	3	<0.01
Total carbon (%DM)	33.5±1.4	31.1±1.3	2	0.24
Total nitrogen (%DM)	2.0±0.0	1.50±0.0	2	<0.01
Ca (g. kg^{-1} DM)	28.92±0.17	51.51± 2.99	2	0.06
Fe (g. kg^{-1} DM)	8.40±0.03	12.78±0.89	2	0.09
Mg (g. kg^{-1} DM)	4.91±0.03	4.12±0.37	2	0.19
K (g. kg^{-1} DM)	7.50±0.50	11.42±0.03	2	0.05
Na (g. kg^{-1} DM)	5.28±0.45	5.36±0.07	2	0.8
P (g. kg^{-1} DM)	9.07±0.18	5.21±0.10	2	0.03
S (g. kg^{-1} DM)	7.37±0.30	5.83±0.13	2	0.05
Mn (mg. kg^{-1} DM)	186.72±4.40	222.74±9.69	2	0.07
Zn (mg. kg^{-1} DM)	360.29±14.71	406.5±49.25	2	0.31
Cu (mg. kg^{-1} DM)	202.10±15.64	118.82±0.64	2	0.09
NH_4 (mg. kg^{-1} DM)	57.50±14	77.13±2.95	2	0.35
NO_3 (mg. kg^{-1} DM)	5.35±0.66	7.08±0.14	2	0.13

[1] Mean ± one standard deviation.
[2] Number of samples.

After collection of the two main feedstocks, eight different mixtures with different ratios of polished digestate to composted OFMSW were prepared. The mixtures were tested for free air space (FAS) and moisture content (MC). The results showed that no amendment was required to adjust FAS, however; water was added to increase the MC in some of the reactors. The amounts of material used in each reactor are presented in Table 5.3.

Table 5.3. Composition and amount of the materials in the reactors.

Reactor ID	Polished digestate (%, ww[1])	Composted OFMSW (%, ww)	Polished digestate (kg)	Composted OFMSW (kg)	Water (kg)	Start-up mass (kg)
C0	0	100	0	11.36	1.70	13.06
C20	20	80	2.13	8.53	1.06	11.72
C30	30	70	3.17	7.40	0.72	11.29
C40	40	60	4.41	6.61	1.22	12.24
C50	50	50	6.24	6.24	1.28	13.76
C60	60	40	6.87	4.58	1.00	12.44
C80	80	20	8.80	2.20	0.22	11.22
C100	100	0	10.04	0.00	0.00	10.04

[1] Wet weight.

5.2.3 Analytical methods

The analyses conducted during the experiment were categorized into three main groups: (1) feedstock characterization, (2) process monitoring, and (3) stability and maturity indices. Parameters used to characterize the feedstock mixtures were free air space (FAS), bulk density (BD), moisture content (MC), total solids (TS), organic matter (OM), pH, electrical conductivity (EC), C:N ratio, ammonium, nitrate and nutrient contents.

Process monitoring focused on temperature, MC, TS, OM, pH, and EC. The stability and maturity indices were C:N ratio, respirometry, Solvita®, ammonium, and nitrate. These indices were tracked to determine the amount of time it took to reach the composting process completion targets. The list of all selected analyses, number of replicates and their test methods is presented in Table 5.4.

Each reactor was sampled once every 20-25 days. The analyses were performed on representative samples obtained by mixing sub-samples taken from different points (top, bottom, middle, and corners) of the bulk material, after unloading the reactor.

Before start-up of the composting experiment, the free air space (FAS) and MC of each mixture was determined and adjusted as needed. FAS was calculated from the BD (wet basis) value according to the following equation (Agnew et al. 2003):

FAS (%) = 100-0.0889BD

The pH and electrical conductivity (EC) were determined on feedstock slurry of 1:10 (feedstock: water), wet mass basis. The total carbon and total nitrogen of oven-dried samples were measured using a Leco TruSpec CN Analyzer according to the method specified by the manufacturer. The temperature in each reactor and chamber was recorded in ten-minute intervals (the average of ten readings within the ten minutes) during the experimental runs. The temperature data were used to create relative heat generation (RHG) values (Larsen and McCartney 2000). The RHG value was calculated using the following equation:

$$\mathrm{RHG} = \int_0^t (\mathrm{T_{reactor}} - \mathrm{T_{chamber}}).\,\mathrm{dt}$$

where $T_{reactor}$ and $T_{chamber}$ are the reactor and chamber temperatures (°C), respectively and t is the duration of the experiment (hour). Respirometry was conducted using a Micro-Oxymax (ER-10) respirometer based on the TMECC 05.08-A method (TMECC 2002). The specific oxygen uptake rate (SOUR) was calculated based on the average value of the instantaneous respiration taken during the 24h of the most intense biological activity (Adani et al. 2004). Solvita® stability and maturity tests were conducted at room temperature for four hours according to the instruction manual (Woods End 2002). Ammonium nitrogen and nitrate nitrogen was extracted with a 2 M KCL in a 1:10 (w/v, sample/extractant) and analyzed with a WestCo SmartChem 200 Discrete Analyzer (O'Dell 1993). Nutrient contents (Ca, Fe, Mg, K, Na, P, S, Mn, Zn and Cu) were measured by inductively coupled plasma-optical emission spectroscopy (ICP-OES, iCAP 6000 Thermo Fisher Scientific. 2007 Cambridge, UK) following HNO_3 digestion.

Table 5.4. Test methods used and stability and maturity end point targets.

	Parameter	Units	Stable/mature[1]	n[6]	Test method
Monitoring	BD	$kg.m^{-3}$	NA[2]	3	TMECC 03.01A
	TS	%, ww	NA	3	TMECC03.09
	OM	%, dw	NA	3	TMECC05.07
	pH	Unitless	NA	3	TMECC 04.11
	EC	$\mu s.\ cm^{-1}$	NA	3	TMECC 04.10
	Temperature	°C	<8[3]	-	-
Stability/ maturity	C/N	Unitless	<25	3	-[4]
	SOUR	mg $O_2.g^{-1}$ OM. d^{-1}	<10	1	TMECC 05.08-A
	Solvita® index	Solvita color code	7-8	1	TMECC 05.08-E
	NH_4	mg NH_4. kg^{-1} dw	<500	2	NRAL-105[5]
	NH_4/NO_3	Unitless	<3	2	NRAL-105

[1] stability and maturity parameter values were adopted from CCQC (2001) and TMECC (2002, 2005).
[2] Not applicable.
[3] Temperature changes.
[4] The C/N ratio measured using a Leco TruSpec CN Analyzer according to the method specified by the manufacturer.
[5] Method NRAL-105 used for the extraction and NH_4 & NO_3 were analyzed according to the method specified by the manufacturer (WestCo SmartChem 200 Discrete Analyzer).
[6] Number of samples.

5.3 Results and discussion

In this section, the typical performance parameters (temperature, relative heat generation (RHG), relative OM removal (ROR), and specific oxygen uptake rate (SOUR)), and chemical parameters (inorganic nitrogen, pH, EC, Solvita®, and total C_{bio}) will be discussed and then the correlations among process and maturity indices and possible reasons associated with the observations will be explained. It should be mentioned that for clarity, the trends of three selected composters, two controls (C0 and C100) and the one in the middle (C50), were presented in the following graphs. Further information regarding all other reactors is presented in Appendix E.

5.3.1 Process performance parameters (temperature, RHG, ROR, and SOUR)

Temperature, OM removal and SOUR values are typical performance indicators in the composting process as they are all related to the level of biological reactions. Representative trend graphs of temperature, relative heat generation (RHG), relative OM removal (ROR), and

SOUR values for three composters are shown in Figure 5.2. The RHG values were calculated from the temperature differences between the reactors and the environmental chamber, as previously described. ROR is defined as the total OM removed during composting per OM added at the first day of loading in each composter. The SOUR values were obtained by running the respirometry test.

In all reactors, the temperature rapidly rose after start-up and no lag phase was observed. As expected, the RHG curves were proportional to the available biodegradable substrates, i.e. C0 > C50 > C100, and organic carbon (ROR) removal was also proportional to the amount of initial degradable feedstock.

To investigate compost stability, SOUR values were compared to a stability threshold end point of 400 mg O_2.kg OM^{-1}. h^{-1} (CCME 2005). Both the composted OFMSW and polished digestate were above stability limits with SOUR values of 2014 and 1230 mg O_2.kg OM^{-1}. h^{-1}, respectively. This indicated that the biological treatment time was insufficient for both feedstocks to reach their stability end points. The differences observed between the feedstocks can be due to different reasons. Firstly, because they were treated with different retention times (21 days for the composted OFSMW versus 56 days for the polished digestate). Secondly, the composted OFMSW was treated in the full-scale process, while the polished digestate was prepared by running the pilot-scale reactor. Overall, the SOUR values decreased at a higher rate during the first twenty days in all the reactors. However, as expected from ROR and RHG trends, the decreasing rate was higher in the reactors with lower concentrations of polished digestate (C0 > C50 > C100).

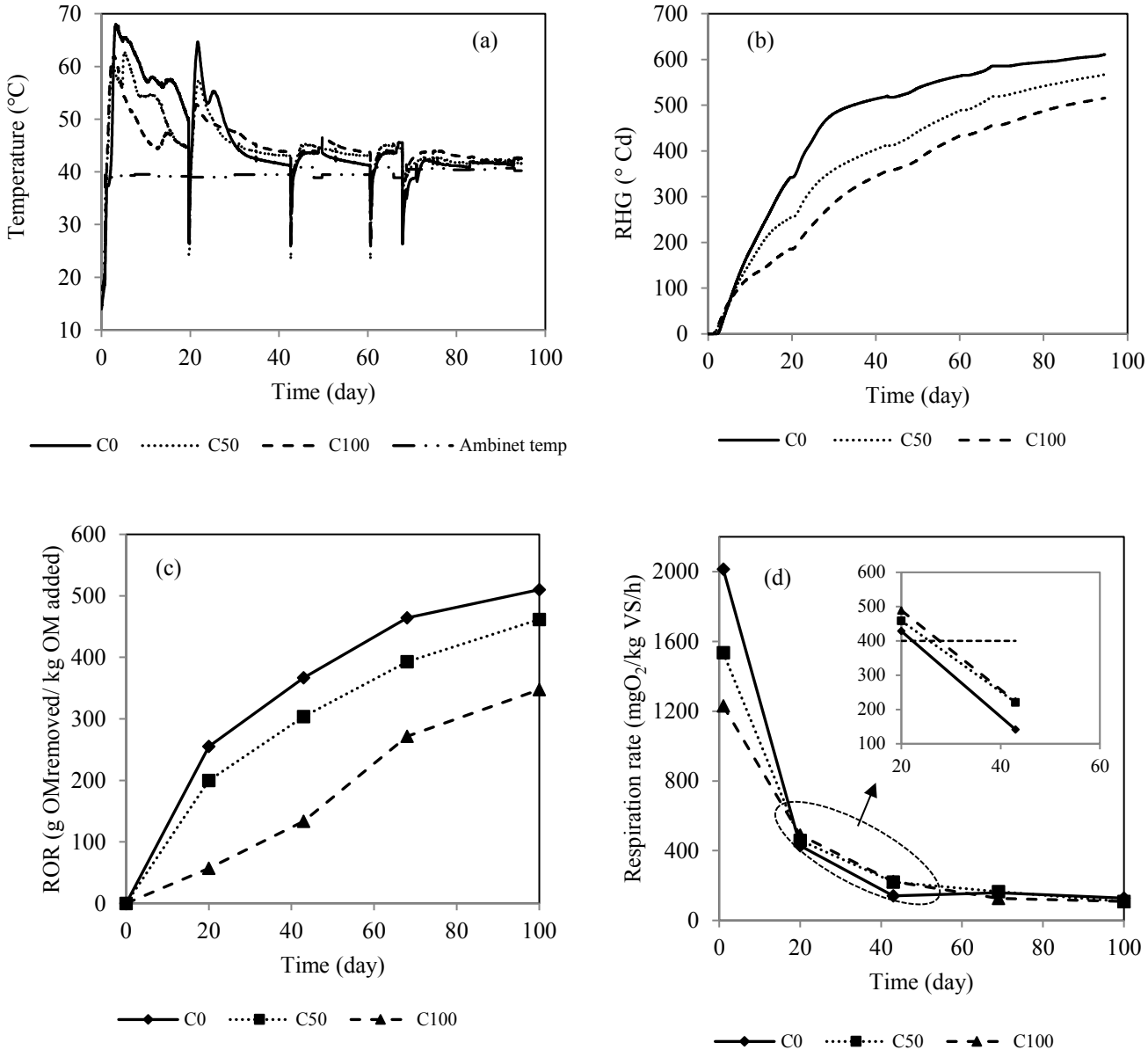


Figure 5.2. (a) Temperature, **(b)** Relative heat generation (RHG), **(c)** Relative OM removal (ROR) and, **(d)** Specific oxygen uptake rate (SOUR) during composting.

The correlation (Pearson correlation coefficient) among the monitored parameters was calculated using Statplus. As shown in Table 5.5, the results indicated that all the parameters were significantly correlated (R=0.74-0.94). This means that any of these parameters could be used as a suitable indicator of the process' performance.

Table 5.5. Correlation coefficients among monitored parameters.

Parameters	ROR	RHG	SOUR	Stability time
ROR	1.00	0.94	-0.81	-0.92
RHG	0.94	1.00	-0.94	-0.85
SOUR	-0.81	-0.94	1.00	-0.74
Stability time	-0.92	-0.85	-0.74	1.00

5.3.2 Inorganic nitrogen (NH_4-N and NO_3-N)

The trends of inorganic nitrogen for the three selected reactors are shown in Figure 5.3. The results of all other reactors are presented in Appendix E, Table E35 and Table E37. The results showed that there was no significant difference between the initial ammonium content observed in the two feedstocks (p-value=0.35). This was probably due to the digestate aeration for seven days before the start-up, which resulted in nitrogen loss through ammonia volatilization. In Chapter 3, a significant difference was found between the digestate and OFMSW (p-value<0.01) in terms of ammonium content and the initial content of ammonium in the digestate (6197 mg. kg^{-1} DM) was observed as one of the possible benefits of digestate co-composting. However, in the current study, the positive effects of ammonium introduced to the system were probably eliminated by over-aeration of the digestate.

As composting progressed, the ammonium concentration increased. The NH_4-N concentration peaked faster (after 20 days) in C0, while that of C50 and C100 peaked at day 43 and 68, respectively. It seemed that ammonification occurred faster in C0 than that of C50 and C100, which was in agreement with the OM degradation rate and temperature evolution. As expected, ammonification was started earlier in the composter with the higher degradation.

In all the composters, ammonium levels decreased after an initial peak while nitrate concentrations increased during the runs. After 100 days of composting, the NH_4-N concentration remained higher in C50 and C100 compared to C0. This was in agreement with the NO_3-N trend (Figure 5.3). NO_3-N formation showed that nitrification had a slower rate in C50 and C100 compared to in C0. Therefore, the nitrification process was probably not completed by the end of curing and resulted in a higher concentration of NH_4-N at day 100. However, because the ammonium peaked earlier in C0, microorganisms associated with nitrification process had a

longer time until the end of the process (from day 20 to 100), and, consequently, the nitrate concentration had its highest value in C0 by the end of composting.

As shown in Figure 5.3, the ammonium loss in all the composters was much higher than the nitrate formation, and the dramatic decrease in NH_4-N did not coincide with a rapid increase in NO_3-N. Therefore, the nitrogen loss during composting was probably governed mainly by ammonia volatilization rather than the nitrification process. This was expected because the chamber temperature was controlled at 40 ºC and the pH value was above 7 during the process, and both the high temperature and pH could limit the nitrification process. Low C:N ratio could be another contributing factor to the loss of ammonium through ammonia volatilization. Microorganisms consume 15-30 parts of carbon for each part of nitrogen. Therefore, at a low C:N ratio, because of the low availability of carbon, excess nitrogen is released to the atmosphere as ammonia.

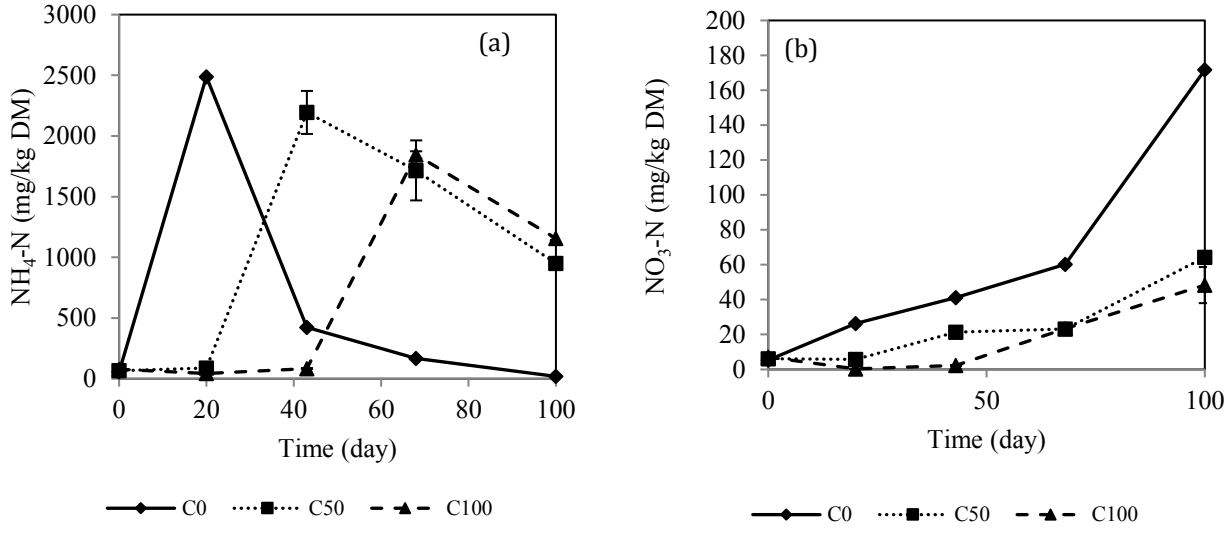


Figure 5.3. (a) NH_4-N, and **(b)** NO_3-N profile during composting.

5.3.3 pH and EC

Figure 5.4 shows the profile of pH and EC during composting. The results of all other reactors are presented in Appendix E, Table E39 and Table E41. As the composting developed, pH increased in all composters. This was probably due to the proteolysis and ammonification because of the organic materials degradation. Since the OM degradation was more intense in C0, the ammonification rate was higher and, consequently, the pH peak was observed earlier (at day 20) compared to the other composters. Interestingly, in all composters, reaching the maximum pH coincided with the highest ammonium concentration. The pH started decreasing in all composters after the peak was observed. This can be explained by ammonium reduction and nitrate formation throughout the process. By day 100 of composting, C0 had the minimum pH among the composters while the ammonium and nitrate concentrations had the lowest and highest values, respectively (Sánchez-Monedero et al. 2001).

The EC reflects the degree of salinity (soluble salts) in the compost and correlated with the concentration of nutrients such as nitrate. At the early stage of composting, the EC decreased in all composters. This was probably due to the consumption of available nutrients by the microorganisms. As the composting progressed, EC started increasing. This can be explained by the formation of nitrate at the later stage of composting. Larger EC values were detected in the composters with higher concentrations of nitrate. A high correlation between EC and nitrate concentrations was also reported in Sánchez-Monedero et al. (2001) study when the effects of nitrogen transformation on EC were investigated.

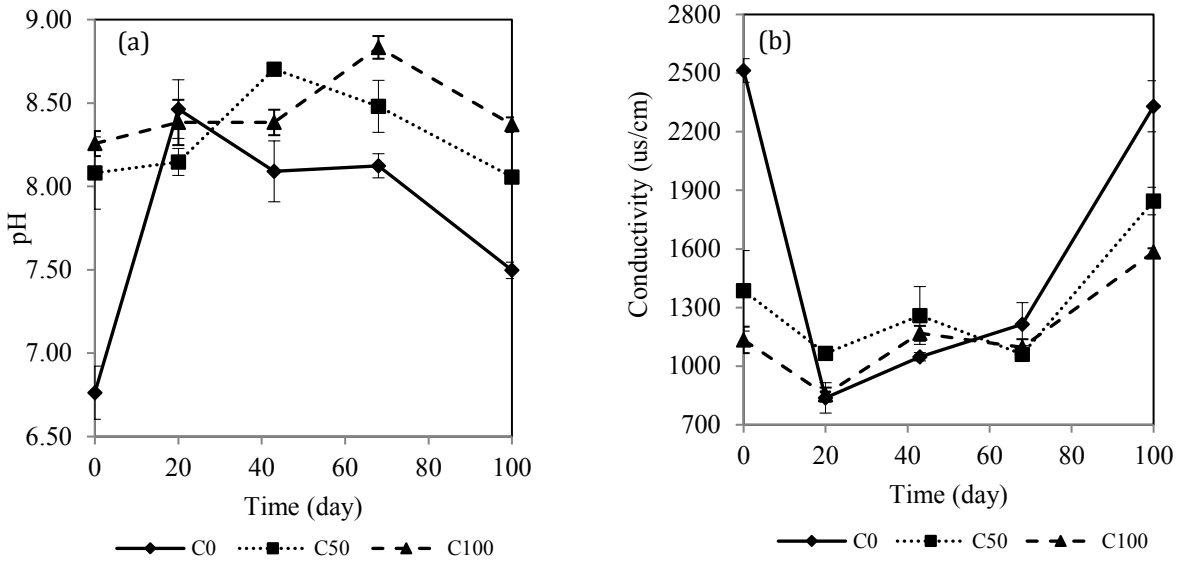


Figure 5.4. (a) pH, and **(b)** EC profile during composting.

5.3.4 Solvita® maturity index

The evolution of the Solvita® index in this study is shown in Table 5.6. The results revealed that the Solvita® index of the feedstock was in the range of 5-6 at the start. This means that the feedstock was ready for curing and a lower aeration was required for further degradation (TMECC 05.08-E, CCQC 2001). This was expected because both of the feedstocks went through the biological processes before being introduced into the composting reactors. As the composting proceeded, the materials became more mature and the Solvita® index increased. Finally, the Solvita® index showed that all the composters reached the maturity index of 7 after 43 days. Finding out the exact day of maturity based on the Solvita® index was not possible since no test was conducted from day 20 to 43. However, a high correlation between this index and the respirometry test (R=-0.96) indicated that the Solvita® index was a suitable indicator to estimate the maturity of the compost in this experiment.

Table 5.6. Evolution of the Solvita® index during the composting process.

Day	C0	C20	C30	C40	C50	C60	C80	C100
0	5	6	5	5	5	5	4	5
20	6	6	6	6	6	6	6	6
43	7	7	7	7	7	7	7	7
68	7	7	7	7	7	7	7	7
100	7	7	7	7	7	7	7	7

5.3.5 Total biodegradable carbon (C_{bio})

The total biodegradable carbon (C_{bio}) in each reactor is shown in Figure 5.5. Observed values were those actually measured during the experiment. The calculated values were determined using the observed C_{bio} values in C0 and C100 feedstocks and the proportion of each used in each reactor. If digestate addition had no effect on the composting process, one would expect the observed and calculated values to be equal. The p-value of 0.34, calculated using one-way ANOVA, showed that there were not significant differences between the calculated (expected) and observed values. Therefore, it can be concluded that the co-composting of digestate did not have any considerable effects on the process. This was expected based on the results observed in the other monitored parameters (ROR and RHG).

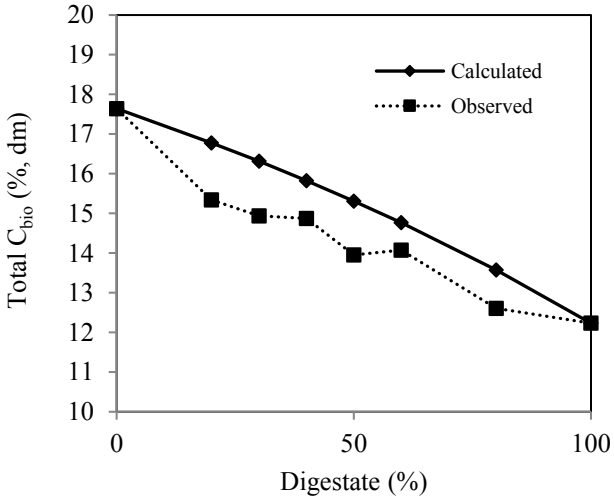


Figure 5.5. Comparison between observed and theoretical (calculated) C_{bio} with different amounts of digestate.

5.3.6 Correlations among the process and maturity indices

Figure 5.6 summarizes the results achieved from key parameters (ROR, RHG, and stability time) plotted against the digestate concentration. Stability time was defined as the day at which each reactor reached the stability end point. All parameters indicated that the composting performance decreased when the digestate concentration increased. Stability time varies in the range of 20 to 27 days. Among the reactors, C0 (with composted OFSMW) and C100 (with polished digestate) had the lowest and highest stability time, respectively. This was probably due to the more intense degradation and higher temperature generation in C0 compared to C100. Overall, it can be concluded that the co-composting of polished digestate and composted OFMSW may not improve the performance of composting. This could be attributed to the physicochemical characteristics of the feedstocks and/or biological properties of the process.

In terms of chemical composition, the total nitrogen and phosphorus, which are the two essential nutrients in biological activities, was significantly higher in the composted OFMSW compared to the polished digestate. This could be one of the possible reasons for the observed better performance in C0 (with the composted OFMSW) compared to C100 (with the polished digestate). Increasing the microbial activities and improving the respiration rate was also observed in the Brown et al. (1998) study when phosphorus was added during the composting of municipal solid waste.

In Chapter 3, the results showed that the composting could take advantage of the total ammonia nitrogen (TAN) introduced to the system by digestate addition because there was a significant difference in ammonium content between the feedstocks. In this study, the digestate was aerated for about a week before start-up, which caused that large portion of TAN to be volatilized during the aeration. However, even if the digestate was not aerated, there was still doubt about taking advantage of the TAN due to different characteristics between aerated and non-aerated OFMSW.

The other difference of this Chapter compared to the Chapter 3 was the stage of composting in which the digestate was added (time of inoculation). In the previous study, digestate and fresh OFMSW were mixed at the beginning of the aeration phase. Since the OFMSW did not undergo

any biological treatment, it was hypothesized that it might not have a diverse microbial population. On the other hand, the microbial population of the digestate was considered an improvement on the diversity and total number of the microorganisms in the overall process.

However, in the current study, the inoculation happened at the curing stage of composting. Polished digestate was mixed with the composted OFMSW, which was aerated for about three weeks before the experiment. Therefore, it probably had enough high concentrations and diversity of the microorganisms required during the curing phase, and the microbial population of the digestate might not have had significant effects compared to the indigenous microbial population of the composted OFMSW. In addition, since a large portion of the organics available in both the feedstocks was degraded before the start of the process, substrate could become a limiting factor. Therefore, even if digestate addition improved the microbial population, there was not enough substrate for microbial growth and activity.

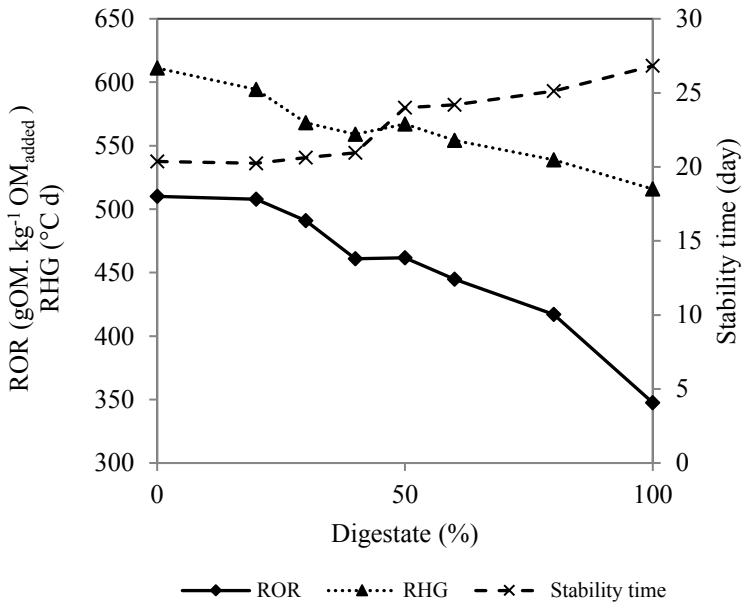


Figure 5.6. Correlation between process and stability parameters.

5.4 Conclusions and recommendation

The effect of adding polished digestate into the curing phase of composting was investigated. Eight different mixtures of 0, 20, 30, 40, 50, 60, 80, and 100% (wet mass) of polished digestate and composted OFMSW were prepared. The results showed that the co-composting of polished digestate and composted OFMSW could not improve the overall performance of composting.

As discussed in chapter 3, in scenario 1 and 2, composting could take advantage of the TAN introduced to the system by digestate addition. However, in scenario 3 and 4, eight days of aeration of the digestate resulted in volatilization of the TAN.

The other hypothesis was to benefit from the microbial population of the digestate during co-composting. However, due to the three weeks aeration of the OFMSW, the composted OFMSW probably had high enough concentrations and diversity of the microorganisms and the microbial population of the digestate might not have significant effects compared to the indigenous microbial population of the composted OFMSW. In addition, because a large portion of the organics available in both the feedstocks was degraded before the start of the process, substrate could become a limiting factor. Therefore, even if digestate addition improved the microbial population, there was not enough substrate for microbial growth and activity.

The results presented in Chapter 3 also showed that the OFMSW could be served as a physicochemical amendment when co-composted with digestate. The OFMSW could increase the FAS, adjust the MC, and balance the C:N ratio of the digestate. However, in this study, because the digestate needed to be aerated separately, woodchips were used to adjust the FAS. In addition, polishing the digestate before the start-up helped to reduce the MC. Moreover, since the OFMSW was also composted, no significant difference was observed between the feedstocks in terms of the C:N ratio. Therefore, polishing the digestate and composting the OFMSW might eliminate the potential benefits of the OFMSW as an amendment.

Overall, comparing four different scenarios based on the results achieved from the current and previous studies, scenario 2 is suggested as the most suitable option for digestate post treatment. In scenario 2, digestate is mixed with the fresh OFMSW at the initial stage (aeration

phase) of composting. The mixing ratio of 20 to 40% (wet mass) is proposed as an optimum mixture to improve the overall performance of the co-composting process. Based on the results of this study, it is also suggested to investigate the effects of unpolished digestate on the curing phase, as scenario 5, in future studies.

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CHAPTER 6: GENERAL CONCLUSIONS AND RECOMMENDATIONS

6.1 Thesis overview

Organic waste constitutes a large portion of waste streams around the world. Residential and non-residential (institutional, commercial, and industrial (ICI)) sectors are the two main sources of organic waste generation. Anaerobic digestion (AD) has been applied in organic waste treatment for decades due to its remarkable advantages such as energy production, greenhouse gas emission reduction and stabilization of organic matter. However, despite all of the benefits, management of the digestate (solid-state by-product) is still a challenge associated with AD.

Among the ICI sectors, Higher Education Institutions (HEIs) usually have a high commitment to develop organic waste processing technologies. The University of Alberta (UAlberta) and Waste Management Services (WMS), have a joint partnership that involves implementing a high solids anaerobic digestion facility (HSADF) at the Edmonton Waste Management Centre (EWMC). Waste characterization in terms of both quality and quantity is required to develop any biotransformation technology. The first objective of this research was to propose a sampling methodology to characterize UAlberta's organic waste stream that would be destined to the HSADF at the EWMC. After collecting of samples, which were representative of organic waste from UAlberta's whole campus, they were characterized for their physical, chemical, and biological properties.

As mentioned earlier, management of high volume of digestate generated during AD is one of the challenges of this technology. Thus, investigation of various options of digestate post-treatment is another objective of this research. Four different options were studied. In the first option, digestate was composted and cured separately. In the second option, digestate was co-composted with different quantities of fresh organic fraction of municipal solid waste (OFMSW) and cured. In the third option, digestate was aerated for about eight days and then cured. Finally, in the fourth scenario, digestate was aerated separately and co-cured with different quantities of composted OFMSW. The most suitable option was suggested comparing the reactors'

performance and stability times in all four options.

6.2 Conclusions

Findings and conclusions drawn from each chapter of dissertation are summarized in the following paragraphs.

In Chapter 2, sampling methodology was proposed to characterize organic waste in terms of physical, chemical, and biological properties. The proposed method can be applied at any Higher Education Institution (HEI) and modified according to the quantification results attained from the waste audit studies for each specific case. Combining the sampling for quantification studies and a typical waste audit could minimize the effort, time, and cost of sampling. UAlberta was selected as a representative of HEI's and case study in this research. Quantification results showed that the organic waste collected from UAlberta could be considered as an appropriate feedstock for biotransformation technologies such as anaerobic digestion and composting. However, bulking agent was required if it was to be used as a composting feedstock.

In chapter 3, co-composting of digestate and OFSMW was investigated in terms of physicochemical characteristics. The results revealed that both main feedstocks could take advantage of each other during co-composting process. The trends of organic matter removal and temperature evolution showed that reactors with 20 to 40% (ww) digestate had the best performance in terms of organic matter removal and heat generation. In addition, these reactors reached the stability point in a shorter time (23 to 26 days), which was 30 to 36% faster than controls. OFMSW could benefit from total ammonia nitrogen (TAN) content introduced to the composting by the digestate. TAN concentration up to 5000 $mg.kg^{-1}$ DM could stimulate the process in terms of carbon removal. However, the higher TAN concentration could be detrimental to the microbial activities due to the imbalance between ammonia nitrogen and carbon availability. Moreover, OFMSW could also serve as amendment and improve the physicochemical properties of the digestate by increasing the free air space (FAS), adjusting moisture content (MC), and balancing the C:N ratio required for composting. Results demonstrated that reactors with the mixing ratio of 50% (ww) and lower did not require

woodchips for FAS and MC adjustment and consequently had larger working volumes compared to the ones which required woodchips.

In chapter 4, the linkage between reactor performance and microbial community dynamics was investigated during co-composting of digestate and OFMSW. Based on the pyrosequencing test results, higher microbial diversity was observed in the reactor with higher OM degradation and shorter stability time (C40). It was concluded that a proper mixing ratio of the two substrates (digestate and OFMSW) in C40 probably created the most favourable condition for the species. In addition, *Thermoactinomycetaceae and Actinomycetales,* with higher relative abundance, were the two bacterial orders that might also result in better performance in C40. *Thermoactinomycetaceae* is able to degrade cellulose and solubilize lignin compounds and *Actinomycetales* participates in degradation of hardly degradable polysaccharides such as lignin. Also, a more favourable fungal community was observed in C40. *Galactomyces* and *Pichia* were found to have their maximum abundance in C40 at early stage of composting, while *Chaetomium* and *Acremonium* were the two abundant genera at the final stage. The first ones are usually introduced to the composting as inoculum in order to improve the process and the latter ones were reported to contribute to lignin degradation by secreting xylanase. The redundancy analysis (RDA) biplot indicated that among the studied environmental variables, temperature, TAN, and nitrate concentration accounted for much of the major shifts in microbial sequence abundance during co-composting process.

In chapter 5, co-composting of polished digestate and composted OFMSW was investigated. No specific effect was observed in co-composting of these two feedstocks and addition of digestate to the composted OFMSW at the curing phase was not found to be favorable. Based on monitored parameters, the composting performance decreased when the digestate portion increased. Unlike unpolished digestate, polished digestate did not have high concentration of TAN to improve the composting since a large portion of TAN volatilized during eight days of aeration. From the biological point of view, there are two possibilities for not detecting inoculation effects from the added digestate. Firstly, indigenous microorganisms might overcome microorganisms introduced to the system by the inoculum. Secondly, substrate could become a limiting factor since a large portion of the organic materials was degraded before the start of the process, during the aeration phase.

Overall, comparing four different scenarios investigated in chapter 3, 4, and 5, scenario 2 is suggested as the most suitable option for digestate post treatment. In this scenario, digestate is mixed with the fresh OFMSW at the initial stage (aeration phase) of composting. The mixing ratio of 20 to 40% (wet mass) is proposed as an optimum mixture to improve the overall performance of the co-composting process. Generally, by reducing the material retention time (MRT) and enhancing the rate of composting, the composting capacity throughput could be increased and energy requirements for aeration during the composting process will be decreased. By implementing the results achieved from this study and conducting a wide study on the operational cost of each individual option (with certain amounts of digestate), valuable data can be attained regarding the economic aspects. This information will assist practitioners when integrating anaerobic digestion technologies into existing composting infrastructure.

6.3 Future research and Recommendations

Based on the results achieved from the investigation of different options, the followings recommendations can be applied in future studies:

1. In this study, the experimental run was conducted on the materials collected only in one season. For example, the anaerobic digestion feedstock for option 1 and 2 was collected in winter and composting feedstock was collected in spring. While the material for option 3 and 4 were collected in summer and fall for AD and composting, respectively. Because of the heterogeneous nature and seasonal variability of the solid waste it is recommended that the effects of seasonal variations on different options of digestate treatment be further studied.

2. Digestate aeration could be one of the reasons that no benefit was observed in option four. Significant loss of moisture content and ammonia nitrogen was observed during eight days of aeration of the digestate. Therefore, further study should take into consideration the impact of unpolished digestate on the curing phase, as option 5.

3. The digestate used in this study was collected from anaerobic digestion after about 6 weeks. The duration of high-solids anaerobic digestion suggested by vendors in the full-scale is usually between 3 to 4 weeks. Therefore, it is worthwhile to investigate 3-4 week old

digestate, which is probably less stabilized compared to that investigated in this study. Finding the optimum balance between the digestate age, methane generation, and composting retention time will result in maximizing the economic potential of an integrated AD and composting facility.

4. In addition to pyrosequencing analysis that determines the relative abundance of microbial population, further microbial techniques such as qPCR are suggested to quantify the total number of each specific species in future studies. Contribution of individual species during the process can be more clearly discussed when the total number of each specific species is identified.

5. In this research, four different scenarios were investigated and compared based on material retention time, physicochemical, and biological properties. Future work should explore the effect of these findings on the full-scale operational costs by conducting economic feasibility studies.

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APPENDIX A: Photographic records

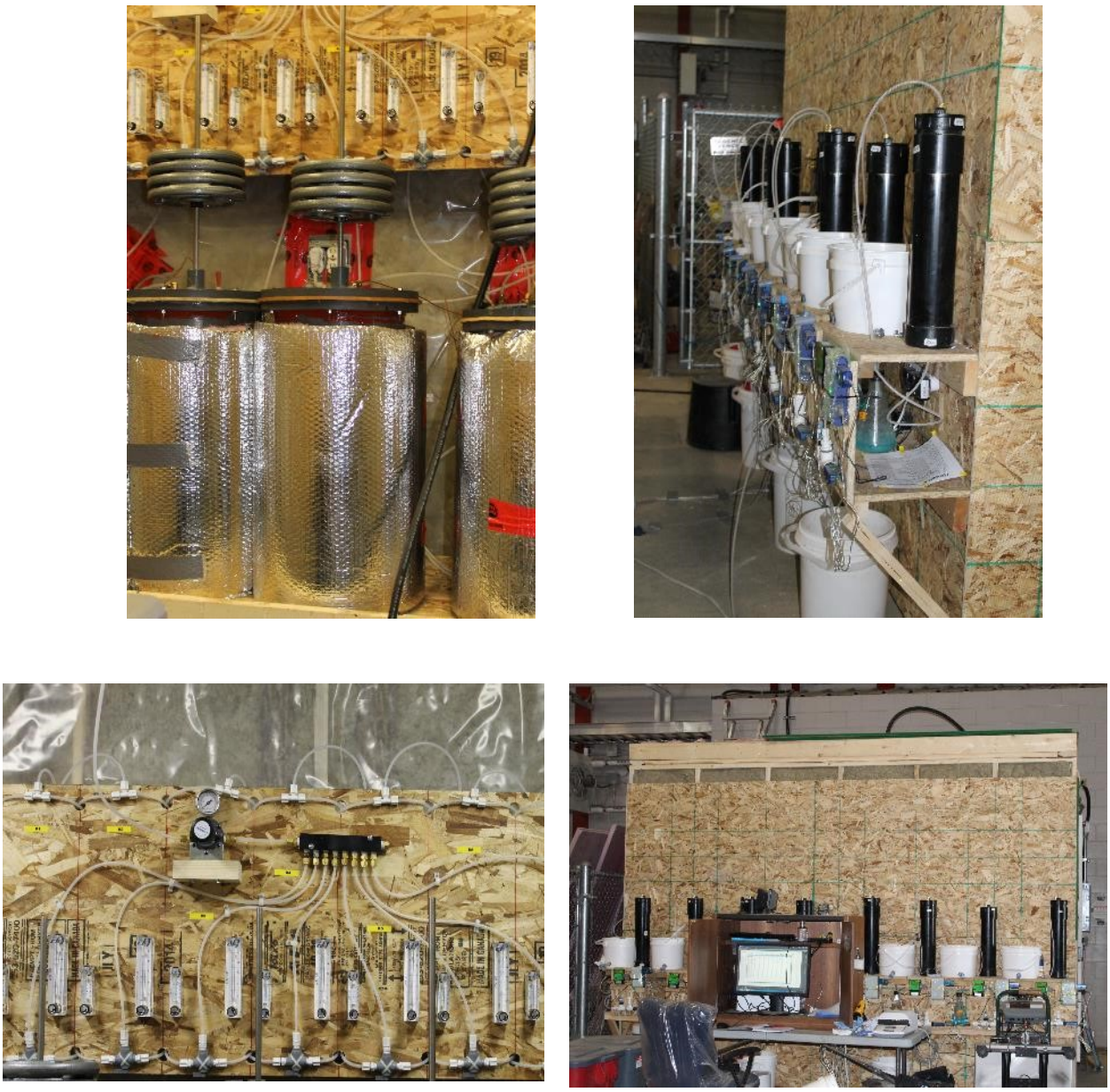


Figure A.1. Commposter reactors with associated apparatus.

Figure A.2. Pilot-scale anaerobic digestion reactor.

APPENDIX B: Chapter 2 Supplementary Data

Appendix B1. Process to estimate the physical/chemical characteristics of organic materials coming from the whole campus

OVERVIEW/APPROACH:

A four-step approach was taken to determine weighted-average physical and chemical characteristics based on building categories and analysis from representative samples. The first step involved selecting representative samples for each building category. The representative samples were selected based on the buildings sampled and analyzed in Arab and McCartney (2014) study. The second step involved estimating the characteristics of representative samples. In the third step, the characteristics of each building category were calculated. In the fourth step, a total weighted average of physical and chemical parameters for the entire UAlberta campus was calculated. The following calculations present each of the four steps using total solids (TS) as an example.

Step 1. Determine the representative samples for each building category:

UAlberta buildings were grouped into five categories based on their functional use: (1) food services, (2) large classrooms, (3) small classrooms, (4) residences and (5) labs; (Yan and McCartney 2012). For each building category, representative samples were selected from buildings sampled in (Arab and McCartney 2014). The selection was based on assumed similarities in building activities. For example, SUB building was considered as one of the representative samples for the food services category due to the large number of food vendors at its location. SUB post consumer was selected as a representative sample for the small offices, residences and labs building categories as small offices, residences and labs buildings were not studied specifically in Arab and McCartney (2014). A summary of building category and representative samples selected in each building category are presented in Table B.1.

Table B.1. List of UAlberta Building Category and representative samples

Building category	Representative samples
1. Food services	SUB, HUB, CAB, LC
2. Large classrooms	ECHA and ED
3. Small offices	SUB post consumer
4. Residences	SUB post consumer
5. Labs	SUB post consumer

Step 2. Determine the weighted mean parameter value for representative samples:

(1) Givens:

Table B.2: Student Union Building (SUB) organic waste amounts (Yan and McCartney 2014) and the physical/chemical test results (Arab and McCartney 2014).

- This table represents the list of subcategory samples (food vendors) that were sampled in SUB, amount of organic waste collected from each vendor, and the mean value of physical and chemical parameters for each vendor.

Table B.3: Amount of source separated organics (SSO) and landfill-bound organics (LBO) and total amount of organics in each building sampled in the 2012 audit (Yan and McCartney 2014).

- This table does not include SSO, LBO, and total amounts from the SUB.

Table B.4 Physical and chemical test results from the other buildings sampled (Arab and McCartney 2014).

- This table represents the mean value of physical and chemical parameters for SSO and LBO streams in each building sampled, except SUB.

Table B.2. Organics amount and Physical and Chemical Characteristics of Subcategory Samples in SUB.

Sample ID	SUB building Sample		Organic waste amount (kg)	BD (kg.m^{-3})	TS (%)	VS (%)	pH	Conductivity (mS.cm^{-1})	C/N
1	Pre-consumer	**Juicy**	17.46	278	30	96	4.1	6.8	21
3		**LE**	336.17	383	28	91	4.1	10.9	11
3		**CD**	89.27	651	41	97	4.2	4.1	26
4		**RATT**	122.94	237	39	93	4.1	9.8	11
5		**JJ**	118.46	364	34	97	4.6	3.4	22
6		**TT**	49.05	146	60	60	7.1	5.5	12
7		**Edo**	82.36	245	42	93	4.0	11.9	14
8		**MF**	76.29	145	22	94	4.2	5.8	24
9		**Subway**	64.84	354	15	89	5.0	7.6	14
10	Post-consumer	**P(F+N)**	1220.53	362	32	95	3.8	7.2	21
11		**P(p)**	206.76	41	68	97	7.4	0.5	46
Total			2384.13						

Table B.3. Amount of SSO and LBO in Each Building, except SUB.

Building	SSO (kg)	LBO (kg)	Total (kg)
FC	0	165.26	165.26
CAB	71.25	31.35	102.6
HUB	0	509.81	509.81
ED	0	147.82	147.82
ECHA	23.84	132.49	156.33
LC	149.87	75.01	224.88

Table B.4. Physical and Chemical Characteristics of SSO and LBO Streams in Each Building, except SUB.

Buildings	BD (kg.m^{-3})	TS (%)	VS (%)	pH	Conductivity (mS.cm^{-1})	C/N
FC (LBO)	706	37	88	5.0	11.4	9
CAB (LBO)	139	36	95	3.8	7.4	20
CAB (SSO)	438	24	94	4.7	6.8	22
HUB (LBO)	401	35	93	3.7	10.7	10
ED (LBO)	267	25	93	3.7	9.7	15
ECHA (LBO)	243	32	96	3.8	8.7	16
ECHA (SSO)	213	30	97	3.9	5.7	20
LC (LBO)	244	37	96	3.8	8.6	11
LC (SSO)	664	25	94	3.8	8.2	15

(2) Calculation:

Weighted mean values for the SUB building was calculated differently than the buildings sampled because SUB had a different data set. Calculations for SUB building are presented in Step 2.1 and other building in Step 2.2, using TS as an example parameter in both cases.

Step 2.1: Determine the weighted mean physical/chemical parameter values for SUB and SUB post-consumer:

The equation used to calculate the total solids value in SUB:

$$TS_{SUB}\ (\%) = \sum_{n=1}^{11}\left(\frac{W_1}{W_t}\times TS_1 + \cdots + \frac{W_{11}}{W_t}\times TS_{11}\right) \qquad \text{Equation (B.1)}$$

TS_{SUB}: overall weighted mean of total solids in SUB (%)
W: amount of waste collected from each vendor (kg; see Table B.2))
TS: total solids of each vendor (%; see Table B.2)
Subscript 1 to 11: Vendor ID (see Table B.2)
W_t: total amount of waste collected from SUB (kg; see Table B.2)

For example, the weighted mean TS value for SUB is:

$$\begin{aligned} TS_{SUB}\ (\%) = \Bigg(&\frac{17.46\ \text{kg}}{2384.13\ \text{kg}}\times 30\% + \frac{336.17\text{kg}}{2384.13\text{kg}}\times 28\% + \frac{89.27\text{kg}}{2384.13\text{kg}}\times 41\% \\ &+ \frac{122.94\text{kg}}{2384.13\text{kg}}\times 39\% + \frac{118.46\text{kg}}{2384.13\text{kg}}\times 34\% + \frac{49.05\text{kg}}{2384.13\text{kg}}\times 60\% \\ &+ \frac{82.36\text{kg}}{2384.13\text{kg}}\times 42\% + \frac{76.29\text{kg}}{2384.13\text{kg}}\times 22\% + \frac{64.84\text{kg}}{2384.13\text{kg}}\times 15\% \\ &+ \frac{1220.53\text{kg}}{2384.13\text{kg}}\times 32\% + \frac{206.76\text{kg}}{2384.13\text{kg}}\times 68\%\Bigg) \end{aligned}$$

$$= 36\%$$

The equation used to calculate the total solids value in SUB post-consumer:

$$TS_{\text{SUB post-consumer}}\ (\%) = \left(\frac{W_1}{W_t} \times TS_1 + \frac{W_2}{W_t} \times TS_2\right) \qquad \text{Equation (B.2)}$$

$TS_{\text{SUB post-consumer}}$: overall weighted mean of total solids in SUB post-consumer (%)
W_1: amount of waste collected from P(F+N) (kg; see Table B.2))
TS_1: total solids of P(F+N) sample (%; see Table B.2)
W_2: amount of waste collected from P(p) (kg; see Table B.2)
TS_1: total solids of P(p) sample (%; see Table B.2)
W_t: total amount of waste collected from P(F+N) and P(p) samples

For example, the weighted mean of TS for SUB post consumer is presented below:

$$TS_{\text{SUB post-consumer}}\ (\%) = \left(\frac{1220.53\ \text{kg}}{(1220.53 + 206.76)\text{kg}} \times 32\% + \frac{206.76\text{kg}}{(1220.53 + 206.76)\text{kg}} \times 68\%\right)$$
$$= 38\%$$

Step 2.2: Determine the weighted mean physical/chemical parameter values for representative samples except the SUB and SUB post-consumer.

The equation used to calculate the total solids value for the representative samples is shown in Equation B.3.

$$TS_t\ (\%) = \left(\frac{W_{SSO}}{W_t} \times TS_{SSO} + \frac{W_{LBO}}{W_t} \times TS_{LBO}\right) \qquad \text{Equation (B.3)}$$

TS_t: overall weighted mean of total solids for the specified sampled building (%)
W_{SSO}: amount of SSO collected from specified sampled building (kg; see Table B.3)
TS_{SSO}: total solids of SSO stream from specified sampled building (%; see Table B.4)
W_{LBO}: amount of LBO collected from specified sampled building (kg; see Table B.3)
TS_{LBO}: total solids of LBO stream from specified sampled building (%; see Table B.4)
W_t: total amount of waste collected from specified sampled building (kg; see Table B.3)

For example, the TS in CAB is presented below:

$$\mathrm{TS_{CAB}}\ (\%) = \left(\frac{71.25\ \mathrm{kg}}{102.60\ \mathrm{kg}} \times 24\% + \frac{31.35\ \mathrm{kg}}{102.60\ \mathrm{kg}} \times 36\%\right) = 27\%$$

(3) Results:

The same procedure of calculation can be applied for the other physical and chemical parameters (i.e. instead of TS use BD, VS, pH, conductivity, or C/N). A summary of the weighted mean values for each representative sample is presented in Table B.5.

Table B.5. Physical and Chemical Characteristics of Representative Samples.

Representative Samples	BD ($kg.m^{-3}$)	TS (%)	VS (%)	pH	Conductivity ($mS.cm^{-1}$)	C/N
SUB	325	36	94	4.3	7.0	21
SUB post-consumer	316	38	95	4.3	6.3	25
FC	706	37	88	5.0	11.4	9
CAB	347	27	94	4.4	7.0	22
HUB	401	35	93	3.7	10.7	10
ED	267	25	93	3.7	9.7	15
ECHA	238	31	96	3.8	8.2	17
LC	524	29	95	3.8	8.4	13

Step 3. Calculation of each building category characteristics

(1) Givens:

- Table C.1 List of UAlberta Building Category (Yan and McCartney 2011) and representative samples, which were selected in order to calculate the characteristics of each building category.

(2) Calculations:

The characteristics in each building category were estimated by determining the average value of its representative samples. For example, the total solids value in the food services building category was the average total solids values from SUB, HUB, CAB, and LC. However, for the building categories with one representative sample, the value of that specified sample was

used (e.g. for small offices category the value of sub-postconsumer was used). The representative samples for each building category is presented in Table B.1 and the physical and chemical characteristics of each representative sample is presented in Table B.5.

For example, the calculation of total solids for the food services building category is presented below:

TS (%) = Average of TS in (SUB, HUB, CAB & LC) samples

$= (36\% + 35\% + 27\% + 29\%)/4$

$= 32\%$

The representative samples for each building category were presented in Table B.1 and the values of TS in sampled buildings were taken from Table B.5.

(3) Results:

The results of physical and chemical characteristics of each building category are summarized in Table B.6.

Table B.6. Physical and Chemical Characteristics of Building Categories.

Building category	BD ($kg.m^{-3}$)	TS (%)	VS (%)	pH	Conductivity ($mS.cm^{-1}$)	C/N
1. Food services	399	32	94	4.1	8.3	16
2. Large classrooms	253	28	95	3.7	8.9	16
3. Small offices	316	38	95	4.3	6.2	25
4. Residences	316	38	95	4.3	6.2	25
5. Labs	316	38	95	4.3	6.2	25

Step 4. Calculation of total weighted-average of physical and chemical parameters for the whole UAlberta campus

After the physical and chemical characteristics of each building category were calculated, the weighted average value for the entire UAlberta campus was calculated.

(1) Givens:

- Table B.6 Physical and Chemical Characteristics of Building Categories (the summary of the results of step 3).
- Table B.7 The estimated amount of organics generated in each building category.

- This table represents the list of building category and estimated amount of organic waste generated in each (Yan and McCartney 2012).

Table B.7. The Estimated Amount of Organics Generated in Each Building Category.

Building category ID	Building category	Organics (tonne)*
1	Food services	588.3
2	Large classrooms	245.6
3	Small offices	57.4
4	Residences	104.2
5	Labs	198.8
Total		1194.3

*Values determined by multiplying the estimated amount of waste generated and its %organics as determined by Yan and McCartney (2012).

(2) Calculations:

The sample equation used to calculate the total weighted-average of total solids in UAlberta is presented in Equation B.4.

$$TS_t\ (\%) = \sum_{n=1}^{5}\left(\frac{W_1}{W_t}\times TS_1 + \cdots + \frac{W_5}{W_t}\times TS_5\right) \qquad \text{Equation (B.4)}$$

TS_t: total weighted-average of total solids (%)

W: amount of waste generated from each building category (kg; see Table B.7)

Subscript 1 to 5: Building category ID (see Table B.7)

TS: total solids in each type of building category (%; see Table B.6)

W_t: total amount of waste collected in all building categories (kg; see Table B.7)

$$TS_t\ (\%) = \left(\frac{588.3\text{kg}}{1194.3\text{kg}}\times 32\% + \frac{245.6\text{kg}}{1194.3\text{kg}}\times 28\% + \frac{57.4\text{kg}}{1194.3\text{kg}}\times 38\% + \frac{104.2\text{kg}}{1194.3\text{kg}}\times 38\% + \frac{198.8\text{kg}}{1194.3\text{kg}}\times 38\%\right)$$

$$= 33\%$$

(3) Results:

The same procedure of calculation can be applied for the other physical and chemical parameters (i.e. instead of TS use BD).

The summary of the total weighted-average values of entire UAlberta is presented in Table B.8.

Table B.8. Total Weighted-average Value of UAlberta.

	BD ($kg.m^{-3}$)	**TS (%)**	**VS (%)**	**pH**	**Conductivity ($mS.cm^{-1}$)**	**C/N**
Total weighted-average	344	33	94	4.1	7.8	19

Appendix B2. Standard Operating Protocol Biochemical Methane Potential (BMP)

1. Principle:

The Biochemical Methane Potential (BMP) test is a widespread method to determine the maximum methane production potential of organic waste.

2. Application:

The BMP test provides an estimate of the maximum amount of methane that could be produced during anaerobic digestion of organic waste. This test is used for a thermophilic anaerobic digestion at 55 ± 2 °C.

3. Abbreviations:

atm	atmospheres
BMP	biomethane potential
EWMCE	Edmonton Waste Management Centre of Excellence
FID	far infrared
GC	gas chromatograph
ISR	inoculum to substrate ratio
MSDS	material safety data sheet
PSI	pounds per square inch
QC	quality control
STP	standard temperature and pressure: 0°C, 1 atmosphere
TCD	thermal conductivity detector
TMECC	Test Methods for the Examination of Composting and Compost
TS	total solids
VS	volatile solids

4. Interferences:

Lignin, cellulose and hemicellulose, which are unready to be biodegraded, will interfere the production of methane.

High pH or low pH will inhibit the growth of particular groups of anaerobic bacteria. Free NH_3 can inhibit the growth of the methane-producing bacteria.

5. Safety

5.1 All EWMCE laboratory personnel are required to wear gloves, buttoned-up lab coats, long pants, and closed-toe shoes when performing this analysis.

5.2 Follow all MSDS handling and storage instructions for any materials used.

5.3 High pressure can be generated during the testing; a full-face mask should be worn.

5.4 Exercise caution when handling glass bottles during the incubation process, as they may be hot. Use heat-resistant gloves where needed.

5.5 Use caution when handling syringes with sharp needles.

5.6 Dispose of sharps (e.g. needles) in a sharps disposal container.

5.7 When placing the crucibles in a furnace or removing them, use appropriate protective personal equipment (e.g. heat-resistant gloves).

5.8 All personnel/visitors must complete EWMCE Health and Safety Orientation before working in the laboratory.

6. Sample Containers and Preservation

6.1 Discrete or composite samples shall be collected in a plastic bottles or bags.

6.2 Due to the long and complex procedure, samples must be frozen at ≤ -10°C in a freezer immediately after sampling to minimize biodegradation.

7. Apparatus

7.1 1 L glass bottles (e.g. 06-414-1D) with high temperature PBT red replacement cap, size GL45 thread (e.g. Corning # 1395-45HTSC)

7.2 1 cm cut of Green Neoprene Stoppers, size 9 (e.g. VWR #59589-290)

7.3 An incubator capable of maintaining 55 °C.

7.4 Convection oven with temperature control of capable of maintaining temperatures of 105 ± 3^{o}C.

7.5 Analytical balance readable to 0.1 mg.

7.6 Muffle furnace: an electric furnace is recommended for igniting the sample. The furnace should be fitted with an indicating pyrometer or thermocouple, so that the required temperature of 575 ± 25 °C can be maintained.

7.7 A pressure gauge (e.g. Cole Palmer) with a 22G1 needle.

7.8 1 mL glass syringe with pressure lock.

7.9 Gas Chromatograph (e.g. Agilent 7890B) with HPLOT-Q capillary, Haysep, and Molesieve columns, TCD and FID detectors, Helium carrier gas, Oxygen gas and Hydrogen gas.

7.10 Purging apparatus

7.11 Shredder (Bear Cat Chipper)

7.12 Blender

7.13 Fume hood

7.14 Pressure gauge (e.g. DPG1000B+15PSIG-5)

8. Reagents and Materials

8.1 $NaHCO_3$ (for pH adjustment)

8.2 Medium: prepare by dissolving the following in ~700 mL of deionized water, adjusting to pH 8.0, and then topping up to 1 L with deionized water:

i. 80 mL resazurin (redox dye; prepared as in 8.3.1);
ii. 4 mL mineral solution 2 (prepared as in 8.3.2);
iii. 0.7 g K_2HPO_4; and
iv. 0.72 g $NaHCO_3$

8.2.1 Resazurin: 100 mg/L as a redox indicator

8.2.2 Mineral solution 2: Dissolve the following compounds in ~700 mL of deionized water, then top up to 1 L with deionized water:

10 g $(NH_4)_6Mo_7O_{24}$-$4H_2O$
0.1 g $ZnSO_4$-$7H_2O$
0.3 g H_3BO_3
1.5 g $FeCl_2$-$4H_2O$
10 g $CoCl_2$-$6H_2O$
0.03 g $MnCl_2$-$4H_2O$
0.03 g $NiCl_2$-$6H_2O$
0.1 g $Al(SO_4)_2$-$12H_2O$

8.2.3 Sulfide solution: 100 mM (24 g/L) Na_2S-$9H_2O$ (anoxic, autoclaved)

8.3 Inoculum: Using fresh sample of anaerobic digester sludge (effluent) from the EPCOR's Gold Bar Wastewater Treatment Plant.

8.4 Substrate: organic waste

8.5 Sodium acetate: prepare an anoxic aqueous stock solution of 1M concentration. Add 2 mL to the positive control cultures (step 13.2).

9. Sampling and Sample Preparation

9.1 Collect representative samples of organic wastes, strictly following an applicable sampling protocol.

9.2 After sampling, reduce the sample particle size using a Bear Cat Chipper shredder with a 3.5 cm screen size.

9.3 Place the size-reduced sample into self-sealing plastic bags (e.g. Ziploc bags). Remove excess air in the bag by the action of squeezing to minimize the occurrence of aerobic processes during storage.

9.4 Take a representative sample for determination of the fraction of total solids (TS_o).

9.5 Dilute the shredded sample to $TS_f = 0.10$ (10%) by adding deionized water.

9.5.1. Required amount of water for 50 g of sample:

$$\frac{50\ g \times \mathrm{TS_o}}{50\ g\ +\ Required\ water\ (g)} = 0.10 = \mathrm{TS_f} \qquad \text{Equation (B.5)}$$

$$Required\ water\ (g) = \frac{(50\ g \times \mathrm{TS_o})\ -5\ g}{0.10} \qquad \text{Equation (B.6)}$$

9.6 Blend the diluted sample with a blender at a high-speed for about 5 minutes.

9.7 If immediate determination of the methane potential is not possible, store the sample (after finishing step 9.6) at ≤ -18 °C.

10. Procedure

10.1 Determine total solids (TS) and volatile solids (VS) of both substrate and inoculum. Refer to appropriate SOPs, based on TMECC 03.09-A and 05.07-A, respectively, for determining TS and VS.

10.2 In a test bottle, add 50 mL of the prepared solution from steps 9.5 and 9.6 (TS = 10%).

10.3 Add 50 mL of medium.

10.4 Determine the inoculum required to reach the ISR (inoculum to substrate ratio, VS based) value of ≥2, by the following formulas:

Minimum required inoculum:

$$\frac{VS_{Inoculum}}{VS_{Substrate}} = 2 \qquad \text{Equation (B.7)}$$

$$\text{Required } \mathrm{VS_{Inoculum}}(g) = 2 \cdot \mathrm{VS_{Substrate}}(g) \qquad \text{Equation (B.8)}$$
$$= 2{\times}50 \text{ g}{\times}10\%{\times}\mathrm{VS_{Substrate}}(\%)$$
$$= 10\mathrm{VS_{Substrate}}(\%)$$

Where;
VS $_{\text{Substrate}}$ (%) is the volatile solids content as a percentage of substrate total solids (TS = 50 g x 10%), as determined in steps 9.5, 10.1 and 10.2.

$$V_{Inoculum}(mL) = \frac{VS_{inoculum}(g)}{VS_{inoculum}\ (\frac{g}{L})} \times 1000(\frac{mL}{L}) \qquad \text{Equation (B.9)}$$

Where,
VS $_{\text{inoculum}}$ (g) is calculated in Equation (B.7)
VS $_{\text{inoculum}}$ (g/L) was determined in step 10.1.

10.5 Conditioning the inoculum

10.5.1. Mix the inoculum well by turning the container upside down a few times.

10.6 Take the required amount of inoculum calculated in step 10.4 of the well mixed inoculum. (for example, if the substrate VS = 80% and inoculum VS = 20 g/L, 400 mL of inoculum is required to reach ISR = 2).

10.6.1. Mix the substrate and inoculum well by inverting the test bottle several times.

10.7 Measure the pH after the complete mixing with a pH meter or pH strips.

10.8 Adjust the pH to the range of 6.8 to 7.2 with $NaHCO_3$.

10.9 Seal the bottle.

10.10 Follow steps 10.1 to 10.9 for each substrate sample in duplicate.

10.11 Purge the headspace of all samples with N_2 to a pressure of 5 PSI.

10.12 Incubate the cultures at 55 °C in the dark, using a shaker incubator. Continue the incubation for the duration of the BMP test.

10.13 Before completing the following steps, make sure a GC is ready for analysis.

10.14 After incubation, withdraw 0.1 mL of gas from the headspace of the test bottle using a gas tight syringe. Directly inject to a GC.

10.15 It is necessary to release gas during the experiment to avoid build-up of excessive pressure in the reactor bottle leading to leakage of gas. The pressure should be measured by the pressure gauge daily and always be kept below 10 PSIG (24.69 PSI or 1.68 atm).

10.15.1. By inserting a needle in the rubber stopper, the pressure can be released. This should be done under a hood and the amount released is calculated from measurement of the methane content in the headspace of the reactor before and after the release. (Equation (B.13))

10.15.2. During the first week the gas should be released 3–4 times (i.e. approximately every 1 to 2 days) due to very high gas production. Later the gas can be released only occasionally (e.g. every 2 to 4 days).

11. Calculations

11.1 The amount of CH_4 is determined based on the volume of the headspace of each reactor and CH_4-content per 0.1 mL of headspace measured directly by the GC.

11.2 The discrete CH_4 measurements, including the gas releases as determined in 10.15.1, are converted into accumulated CH_4 as a function of incubation time.

11.3 The methane production from the inoculum (blanks) is subtracted from the methane production of the waste samples. The result thus represents only the methane production from the waste and not from the inoculum.

11.4 The pressures in the test vessel/bottle (P_t, in PSIG) are recorded with the pressure gauge at every measurement of methane before and after the pressure release. These values are used to determine the volume of methane generated at standard temperature and pressure, as per Equation (B.11).

$$P_t = Bottle\ pressure\ (PSI) = Pressure\ gauge\ (PSIG) + Atmospheric\ pressure\ (e.g.\ 14.69\ PSI)$$ Equation (B.10)

$$V_{STP} = \frac{P_t . V_t . T_{STP}}{T_t P_{STP}}$$ Equation (B.11)

where
V_{STP} = Volume of methane at standard conditions (STP: 0°C, 14.69 PSI/1 atm), mL
P_t = pressure in the test vessel, PSI (Equation (B.10))
V_t = volume of methane in test vessel under test conditions = measured methane content (%)* headspace, mL (Equation (B.12)).
T_{STP} = 273°K = 0°C
T_t = test temperature, 328°K = 55°C
P_{STP} = 14.69 PSI (1 atm)

$$Headspace\ volume\ (ml) = Bottle\ volume\ (ml) - Sample\ volume\ (ml)$$ Equation (B.12)

The bottle volume is measured by filling it with water.

$$V_{Released} = V_{before\ @\ STP} - V_{after\ @\ STP}$$ Equation (B.13)

where
$V_{Released}$ = Volume of methane released (mL)
$V_{before\ @\ STP}$ = Volume of methane in the bottle before release (mL)
$V_{after\ @\ STP}$ = Volume of methane in the bottle after release (mL)

$$V_{accumulated} = (V_{generated} - V_{inoculum}) + V_{released}$$ Equation (B.14)

12. Report

The results are reported as the cumulative methane generation (mL) per gram of added VS at standard conditions (STP: 0°C, 1 atm).

13. Quality Control

13.1 Blank sample

13.1.1. The blank is a mixture of the medium and inoculum without any substrate. This type of control is required in order to calculate the inoculum biodegradability. The amount of media and inoculum added to the blank should be the same as the amounts in the test bottles.

13.2 Control sample (QC)

13.2.1. Prepare a positive control by adding a known amount (2 mL) of 1 M sodium acetate (prepared in 8.5), which is a known biodegradable substrate, to the mixture

of medium and inoculum. The amount of media and inoculum added to the control sample should be the same as the amounts in the test bottles.

13.2.2. The gross performance of the inoculum is indicated with the positive control.

APPENDIX C: Chapter 3 Supplementary Data

Appendix C1: Sampling methodology to collect sample from waste Piles

According to ASTM D6009-12 (Standard Guide for Sampling Waste Piles), sampling strategies available for waste piles include:

1. Judgmental or directed sampling (e.g. worst case condition in the pile)
2. **Simple random sampling (heterogeneous)**
3. Stratified random sampling (homogenous subgroup)
4. Systematic grid sampling
5. Systematic sampling over time

A simple random approach could use a grid with random grids selected for sample collection. Note that the grid size could be selected based on the number of samples that are required (some guidance suggests having at least ten times the number of grids as samples required).

In the following paragraph sampling methodology used to collect representative samples from a pile was explained. Source separated organics (SSO) collected from three institutional, commercial and industrial (ICI) sectors was selected as an example. Sampling was conducted for pilot-scale anaerobic digestion run in March 2015. Based on the City of Edmonton records, the SSO were collected twice a week, Tuesdays and Fridays, from various ICI locations. In our sampling day (March 6, 2015) SSO was collected from three locations:

1. The Organic Box (a food distribution business),
2. High Level Diner (a restaurant), and
3. Commerce Place (a food court within a commercial building downtown).

The collection frequency of the first source was once per week and the second and third locations had two times collection frequency per week. 1100kg SSO was collected from these three sources on the specified collection day.

Number of samples

According to ASTM D5231-92, the number of sorting samples (n) required to achieve a desired level of measurement precision is a function of the component(s) under consideration and the confidence level. The governing equation for n is as follows:

$$n = (\frac{t.s}{e.x})^2$$

where:
t = student t statistic corresponding to the desired level of confidence,
s = estimated standard deviation,
e = desired level of precision, and
x = estimated mean.

For confidence interval=90%, t (n=∞)= 1.645
It was assumed that the amount of organics in the ICI SSO stream was 80%±10%. Therefore, x=0.8 and s=0.1.
The precision value (e) was considered 5%.

$$n = (\frac{t.s}{e.x})^2 = (\frac{1.645*0.1}{0.05*0.8})^2 = 16.91$$

The t value for n=17 is 1.745.
Therefore:

$$n = (\frac{t.s}{e.x})^2 = (\frac{1.745*0.1}{0.05*0.8})^2 = 19.05$$

The required number of sample was calculated as **20**.

Steps of sampling:

1. Unload the truck and debagging
2. Distribute the sample on a clean surface (3.6m*4.4m) with the same level.
3. Build grids with the size of (40cm*40cm) using the measuring tape and rope.
4. Generate 20 random numbers from 1 to 99.
5. Collect the samples from the assigned girds.
6. Mix all the collected samples.
7. Reduce sample size with quartering method.

Steps of sampling are shown in Figure C1-C5. As mentioned earlier, the samples were SSO stream collected from three ICI sectors from City of Edmonton in March 2015.

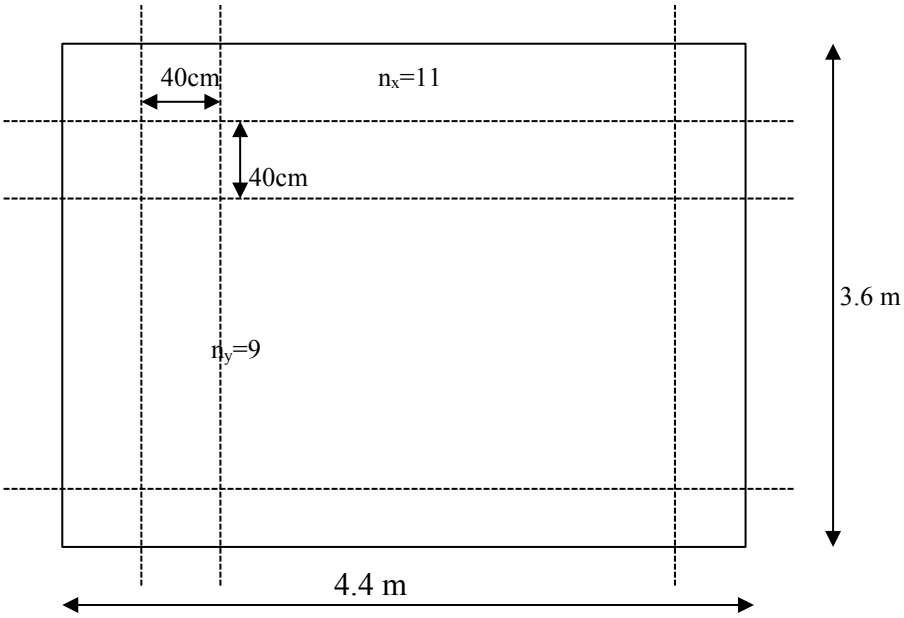


Figure C.1. Unprocessed source separated organics sampling steps (step1, debagging).

Figure C.2. Unprocessed source separated organics sampling steps (step2, distribution).

Figure C.3. Unprocessed source separated organics sampling steps (step3.a, making grids).

Figure C.4. Unprocessed source separated organics sampling steps (step3.b, making grids).

Figure C.5. Unprocessed source separated organics sampling steps (step4, quartering).

Appendix C2: Free air space (FAS) calculation

Free air space (FAS) was calculated using the device shown in Figure C6. This device is equipped with an air cylinder that is able to compact the compost to mimic different depths of a pile while running tests. After compacting the sample with a specific pressure, sample volume and bulk density (BD) is calculated and FAS can be estimated using the following formula:

FAS (%)=100-0.0889* bulk density (Agnew et al., 2003)

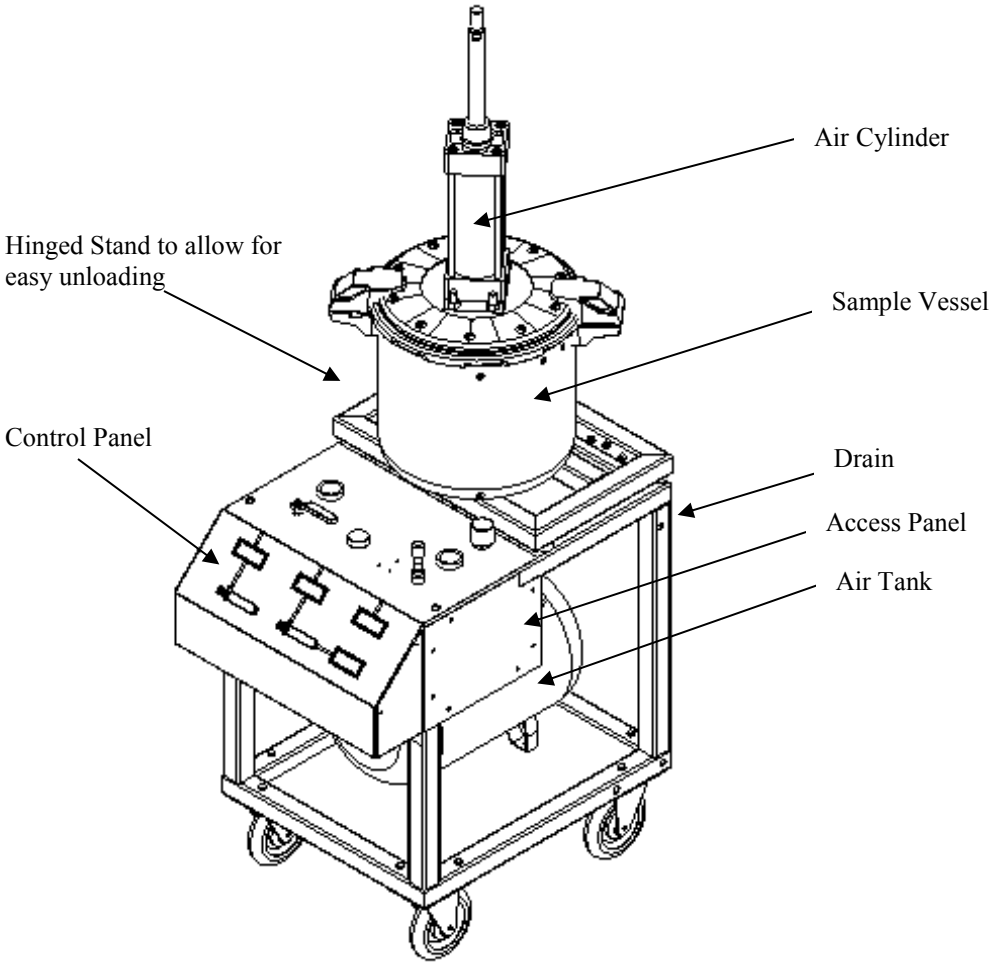


Figure C.6. Free air space (FAS) measurement apparatus (Nicholson M. 2006, user manual).

In the following paragraphs, steps conducted to measure the woodchips required in each reactor was explained.

Steps:

1. Fill the sample vessel.
2. Measure the Bulk density (BD_1).

   BD = M/V
   BD: Bulk density of the sample (kg/m^3)
   M: Sample weight (kg)
   V: Sample vessel volume (m^3), 0.14805 m^3

3. Measure the pressure (pa) required to simulate height of 1.6m. This height is the middle height of full-scale aeration bay in Edmonton composting facility (ECF).

   $P=BD*g*h_1$
   P: required pressure to simulated height of 1.6m (pa)
   BD: bulk density of the sample calculated in step 2.
   g: 9.81 m/s^2
   h_1:1.6 m

4. Measure the force (N) required applying the pressure calculated in step3.
   F = P.A
   P: pressure calculated in step3.
   A: area of the sample vessel (m^2), $740*10^{-4}$ m^2

5. Apply the required force calculated in step 4 into the vessel.

6. Monitor the height changes in the sample vessel and record the height after 5 minutes (h_2).

7. The BD_2 (kg/m^3) was calculated based on the height after the compaction (h_2).

   $BD_2=M/A.h_2$
   M: Sample weight (kg)
   A: area of the sample vessel (m^2), $740*10^{-4}$ m^2
   h_2: the height after five minutes of compaction (m)

8. Re-read the height, h_3 (usually after 15 minutes, this may be changed based on the compaction rate in each sample)

9. The BD_3 (kg/m^3) was calculated based on the height after the compaction (h_3).

   $BD_3=M/A.h_3$
   M: Sample weight (kg)
   A: area of the sample vessel (m^2), $740*10^{-4}$ m^2
   h_3: height after 15minutes of compaction (m)

10. Free air space (FAS) was calculated based on the following formula;

FAS (%)=100-0.0889*BD_3 (Agnew et al., 2003)

11. Woodchips required in each composter was calculated based on the FAS calculated in step 10 and moisture content (MC). In order to have an appropriate condition for microorganisms during composting, it was recommended to adjust FAS>30% and MC<55%. MC in each reactor was calculated based on the mass balance and the MC of three main feedstocks, which are shown in Table C1.

12. The final values of FAS and MC at different amount of woodchips in each composting reactor are presented in Table C2. Based on the MC and FAS results, it can be concluded that woodchips was only required in C75 and C100 and both MC and FAS were in the suitable ranges in the other reactors.

Table C.1. Total solids (TS) of the three main feedstocks at the start-up.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[2] (%)	Ave TS (%)	Ave MC (%)	STD[3]
1	OFMSW (2"-5")[1]	32.47	102.76	72.39	57	43	58	42	1
2		32.20	110.22	78.65	60	40			
3		31.53	129.82	87.71	57	43			
4	Digestate	31.68	434.48	180.18	37	63	37	63	2
5		32.26	395.50	162.02	36	64			
6		32.01	460.40	202.33	40	60			
7	Woodchips	32.61	107.42	101.25	92	8	92	8	0
8		32.54	89.87	85.62	93	7			
9		32.24	97.86	92.82	92	8			

[1] Organic fraction of municipal solid waste with particle size of 2 to 5 inches.
[2] Moisture content.
[3] Standard deviation.

Table C.2. Reactors free air space at different amount of woodchips (WC).

Reactor ID	WC (%)	M[1] (kg)	BD[2] ($kg.m^{-3}$)	P[3] (pa)	F[4] (N)	H[5] (cm)	BD[6] ($kg.m^{-3}$)	FAS[7] (%)	MC[8] (%)
C0	0	2.52	170.2	2727.3	201.8	10.4	327.4	70.9	42.0
C10	0	2.08	140.5	2251.1	166.6	9.4	302.2	73.1	44.1
C20	0	2.70	182.4	2922.1	216.2	10.3	354.2	68.5	46.2
C30	0	2.92	197.2	3160.2	233.9	10.3	383.1	65.9	48.3
C40	0	4.40	297.2	4762.0	352.4	10.8	571.7	49.2	50.4
C50	0	4.24	286.4	4588.8	339.6	11.0	535.5	52.4	52.5
C75	0	6.62	447.1	7164.6	530.2	13.6	657.8	41.5	57.8
C75	3	5.12	345.8	5541.2	410.1	12.9	536.4	52.3	56.1
C75	5	4.76	321.5	5151.6	381.2	12.5	518.7	53.9	55.0
C100	0	11.70	790.3	12662.6	937.0	14.8	1068.3	5.0	63.0
C100	5	6.86	463.4	7424.4	549.4	14.0	662.2	41.1	60.0
C100	10	6.44	435.0	6969.8	515.8	13.8	644.6	42.7	57.3
C100	15	4.86	328.3	5259.8	389.2	15.2	434.9	61.3	54.9

[1] sample mass, [2] Bulk density, sample vessel volume=14.805 liter,
[3] pressure, [4] force, [5] sample height, [6] bulk density after compaction, [7] free air space, [8] Moisture content.

Appendix C3: Supplementary results

Total solids test raw data are presented in Table C3-C12.

Table C.3. Total solids (TS) of the reactors at day 0 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
1	C0	32.39	72.02	51.27	48	52	47	53	1
2		32.24	70.83	47.09	38[3]	62			
3		31.52	70.69	49.57	46	54			
4	C10	31.67	69.30	48.67	45	55	45	55	3
5		32.27	77.77	51.30	42	58			
6		32.03	70.27	50.53	48	52			
7	C20	32.67	82.44	56.36	48	52	48	52	0
8		32.46	67.51	49.11	48	52			
9		32.23	66.75	50.73	54[3]	46			
10	C30	32.29	76.52	53.90	49	51	47	53	1
11		31.65	85.59	57.25	47	53			
12		33.50	65.58	48.06	45	55			
13	C40	32.10	73.43	49.65	42	58	45	55	3
14		32.52	72.96	49.90	43	57			
15		32.44	86.64	59.01	49	51			
16	C50	32.27	93.80	58.89	43	57	44	56	3
17		31.77	88.32	59.00	48	52			
18		32.12	87.51	54.60	41	59			
19	C75	32.52	99.45	61.69	44	56	42	58	2
20		31.88	96.86	59.05	42	58			
21		31.88	104.39	60.54	40	60			
22	C100	32.64	134.76	76.78	43	57	41	59	2
23		31.80	161.87	84.49	41	59			
24		32.31	143.65	76.35	40	60			

[1] Moisture content, [2] Standard deviation.

[3] Contamination (ceramic piece) was found in this sample. Therefore, it was not considered in the average calculation.

Table C.4. Total solids (TS) of the reactors at day 3 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G54	C0	15.54	27.99	22.31	54	46	55	45	1
G3		15.57	28.46	22.85	56	44			
G53	C10	15.60	37.33	27.08	53	47	50	50	3
G55		15.51	34.85	24.68	47	53			
G33	C20	15.69	29.58	22.95	52	48	53	47	1
G49		15.77	24.66	20.59	54	46			
G44	C30	15.71	36.19	25.29	47	53	45	55	2
G47		15.75	36.58	24.66	43	57			
G37	C40	15.59	46.80	29.32	44	56	45	55	1
G32		15.66	49.15	30.94	46	54			
G30	C50	15.63	44.71	29.01	46	54	48	52	2
G17		15.69	52.46	34.37	51	49			
G18	C75	15.61	57.53	34.19	44	56	44	56	1
G51		15.74	56.93	33.37	43	57			
G20	C100	15.51	68.04	38.05	43	57	42	58	1
G21		15.53	61.64	34.20	40	60			

[1] Moisture content, [2] Standard deviation.

Table C.5. Total solids (TS) of the reactors at day 6 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G55	C0	15.58	38.59	27.67	53	47	52	48	1
G51		15.70	36.70	26.49	51	49			
G17	C10	15.70	54.10	27.93	32	68	32	68	0
G49		15.77	62.38	30.64	32	68			
G47	C20	15.75	23.82	20.55	59	41	57	43	3
G21		15.53	30.32	23.46	54	46			
G50	C30	15.76	62.14	38.51	49	51	52	48	3
G21		15.65	49.73	34.34	55	45			
G46	C40	15.64	32.71	23.07	44	56	48	52	4
G19		15.60	39.96	28.32	52	48			
G1	C50	15.76	61.36	37.68	48	52	53	47	5
G4		15.69	46.89	33.52	57	43			
G3	C75	15.57	40.79	27.13	46	54	47	53	1
G44		15.82	34.86	24.90	48	52			
G37	C100	15.67	75.40	43.21	46	54	45	55	1
G33		15.76	65.90	38.08	45	55			

[1] Moisture content, [2] Standard deviation.

Table C.6. Total solids (TS) of the reactors at day 10 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G55	C0	15.6	35.89	25.06	47	53	44	56	3
G17		15.70	35.19	23.68	41	59			
G51	C10	15.74	47.40	26.03	33	67	32	68	0
G61		15.63	79.38	36.24	32	68			
G19	C20	15.59	40.88	27.06	45	55	49	51	4
G46		15.71	31.35	23.91	52	48			
G21	C30	15.54	34.91	25.63	52	48	52	48	0
G50		15.81	43.44	30.03	51	49			
G3	C40	15.63	47.85	32.45	52	48	51	49	1
G1		15.87	55.04	35.69	51	49			
G33	C50	15.74	47.90	30.45	46	54	45	55	1
G44		15.82	48.94	30.46	44	56			
G49	C75	15.76	60.51	34.42	42	58	45	55	3
G4		15.68	61.92	37.86	48	52			
G37	C100	15.67	51.38	31.42	44	56	44	56	0
G47		15.83	54.45	32.67	44	56			

[1] Moisture content, [2] Standard deviation.

Table C.7. Total solids (TS) of the reactors at day 13 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G4	C0	15.69	45.17	27.89	41	59	43	57	2
G49		15.76	46.14	29.43	45	55			
G19	C10	15.60	101.49	41.80	31	69	32	68	1
G21		15.54	110.24	46.68	33	67			
G61	C20	15.65	52.90	33.14	47	53	45	55	1
G51		15.75	53.73	32.46	44	56			
G17	C30	15.71	76.72	44.68	47	53	49	51	1
G55		15.58	63.18	39.29	50	50			
G46	C40	15.71	113.99	59.67	45	55	45	55	0
G3		15.63	125.85	65.27	45	55			
G33	C50	15.85	109.15	54.16	41	59	41	59	0
G1		15.83	86.66	44.81	41	59			
G44	C75	15.81	103.51	54.33	44	56	44	56	0
G50		15.80	81.40	44.49	44	56			
G47	C100	15.87	140.85	72.67	45	55	45	55	0
G37		15.67	104.76	55.38	45	55			

[1] Moisture content, [2] Standard deviation.

Table C.8. Total solids (TS) of the reactors at day 20 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G51	C0	15.74	42.08	27.34	44	56	41	59	3
G19		15.70	50.96	28.90	37	63			
G21	C10	15.56	57.20	31.83	39	61	40	60	1
G49		15.76	52.42	30.75	41	59			
G55	C20	15.57	49.65	30.25	43	57	42	58	1
G61		15.66	47.05	28.80	42	58			
G4	C30	15.69	60.03	36.48	47	53	46	54	1
G19		15.62	52.98	32.52	45	55			
G3	C40	15.62	74.47	43.11	47	53	46	54	0
G1		15.85	83.22	46.98	46	54			
G46	C50	15.71	90.07	44.40	39	61	39	61	0
G50		15.82	63.57	34.45	39	61			
G44	C75	15.84	92.93	52.82	48	52	45	55	3
G33		15.76	108.87	54.62	42	58			
G37	C100	15.68	70.26	39.86	44	56	44	56	1
G47		15.94	73.81	40.72	43	57			

[1] Moisture content, [2] Standard deviation.

Table C.9. Total solids (TS) of the reactors at day 30 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G17	C0	15.68	48.77	31.07	47	53	45	55	1
G19		15.59	48.35	30.00	44	56			
G14	C10	15.70	76.66	41.84	43	57	43	57	1
G55		15.57	73.65	41.09	44	56			
G61	C20	15.63	53.11	33.17	47	53	47	53	0
G3		15.65	49.64	31.41	46	54			
G51	C30	15.75	61.79	38.58	50	50	48	52	1
G1		15.83	65.78	39.37	47	53			
G46	C40	15.71	86.69	49.81	48	52	48	52	0
G50		15.80	76.92	44.68	47	53			
G35	C50	15.57	89.66	44.80	39	61	41	59	1
G21		15.55	89.06	46.66	42	58			
G33	C75	15.75	92.93	51.14	46	54	47	53	1
G44		15.80	99.33	55.97	48	52			
G53	C100	15.63	88.26	48.72	46	54	46	54	0
G18		15.68	82.43	46.45	46	54			

[1] Moisture content, [2] Standard deviation.

Table C.10. Total solids (TS) of the reactors at day 65 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
G51	C0	15.77	41.02	32.56	66	34	66	34	1
G18		15.68	39.24	31.02	65	35			
G17	C10	15.7	42.3	32.72	64	36	65	35	1
G35		15.6	36.13	29.04	65	35			
G21	C20	15.55	34.57	29.65	74	26	73	27	1
G4		15.69	29.75	25.75	72	28			
G49	C30	15.76	50.00	38.72	67	33	66	34	2
G61		15.64	41.58	32.24	64	36			
5	C40	15.76	47.63	34.35	58	42	59	41	1
4		15.83	47.81	35.12	60	40			
6	C50	15.85	60.22	38.93	52	48	53	47	1
3		15.7	60.37	39.96	54	46			
7	C75	15.68	59.62	40.42	56	44	56	44	0
2		15.83	54.96	37.52	55	45			
8	C100	15.65	61.48	42.12	58	42	57	43	1
1		15.68	59.88	40.19	55	45			

[1] Moisture content, [2] Standard deviation.

Table C.11. Total solids (TS) of the reactors at day 100 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC[1] (%)	Ave TS (%)	Ave MC (%)	STD[2]
C28	C0	126.44	147.94	142.23	73	27	75	25	1
E28		113.27	143.12	136.06	76	24			
E23	C10	113.24	134.28	129.69	78	22	78	22	0
E29		113.56	130.43	126.74	78	22			
E35	C20	122.71	156.58	150.34	82	18	81	19	1
C22		125.46	153.92	148.28	80	20			
UA14	C30	71.69	112.42	102.35	75	25	74	26	1
UA13		78.27	109	100.87	74	26			
UA10	C40	69.58	109.37	97.19	69	31	69	31	0
UA15		85.25	124.61	112.39	69	31			
UA11	C50	77.66	126.05	110.69	68	32	69	31	1
UA06		71.81	117.04	103.29	70	30			
UA07	C75	87.03	145.65	126.04	67	33	65	35	2
UA12		80.78	127.52	110.10	63	37			
UA09	C100	80.72	124.49	110.58	68	32	69	31	0
UA08		69.78	114.07	100.34	69	31			

[1] Moisture content, [2] Standard deviation.

Table C.12. Summary of total solids (TS) of the reactors during composting.

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	47±1[1]	45±3	48±0	47±1	45±3	44±3	42±2	41±2
3	55±1	50±3	53±1	45±2	45±1	48±2	44±1	42±1
6	52±1	32±0	57±3	52±3	48±4	53±5	47±1	45±1
10	44±3	32±0	49±4	52±0	51±1	45±1	45±3	44±0
13	43±2	32±1	45±1	49±1	45±0	41±0	44±0	45±0
20	41±3	40±1	42±1	46±1	46±0	39±0	45±3	44±1
30	45±1	43±1	47±0	48±1	48±0	41±1	47±1	46±0
65	66±1	65±1	73±1	66±2	59±1	53±1	56±0	57±1
100	75±1	78±0	81±1	74±1	69±0	69±1	65±2	69±0

[1] Total solids ± standard deviation.

Organic matter test raw data are presented in Table C13-C22.

Table C.13. Organic matter (OM) content of the reactors at day 0 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
e29	C0	113.58	117.72	114.48	78	78	1
c15		67.81	71.36	68.62	77		
e30	C10	115.24	120.25	116.55	74	77	3
c23		69.42	71.54	69.86	79		
c22	C20	125.48	127.65	126.01	76	74	2
c9		71.20	72.58	71.59	72		
e1	C30	114.77	120.91	117.21	60	66	6
c26		68.84	72.34	69.84	71		
c28	C40	126.46	130.02	127.70	65	65	0
J		70.63	75.40	72.31	65		
e28	C50	113.24	121.22	115.98	66	63	2
p		71.63	75.19	73.01	61		
e39	C75	111.60	121.60	115.89	57	57	0
c24		67.42	80.79	74.87	44[2]		
e35	C100	122.69	132.36	127.03	55	54	1
k		66.83	78.34	72.33	52		

[1] Standard deviation.
[2]A piece of glass was found in the sample after ignition. Therefore, this sample was not considered in OM average calculation.

Table C.14. Organic matter (OM) content of the reactors at day 3 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
M	C0	70.18	71.65	70.53	76	74	2
C16		67.13	69.98	67.94	72		
C27	C10	69.14	70.36	69.48	72	71	1
C16		67.13	68.30	67.48	70		
C24	C20	67.40	68.82	67.77	74	73	1
C20		71.19	73.76	71.90	72		
K	C30	66.81	68.82	67.48	67	66	0
J		70.64	73.88	71.74	66		
C15	C40	67.78	73.29	69.73	65	64	1
P		71.59	77.14	73.63	63		
C26	C50	68.84	71.33	69.79	62	63	2
C10		67.89	74.16	70.08	65		
C25	C75	69.63	72.48	70.72	62	59	3
C9		71.16	74.48	72.63	56		
C23	C100	69.37	74.93	71.62	60	57	3
9		126.43	133.10	129.52	54		

[1] Standard deviation.

Table C.15. Organic matter (OM) content of the reactors at day 6 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
C19	C0	70.18	72.65	70.84	73	74	1
C15		67.78	70.33	68.43	75		
C16	C10	67.13	70.91	68.48	64	66	1
C9		71.15	74.60	72.29	67		
J	C20	70.63	73.06	71.31	72	72	0
K		66.81	69.15	67.45	73		
C23	C30	69.36	76.20	71.51	69	67	2
C26		68.84	76.18	71.45	64		
C25	C40	69.64	75.52	71.79	63	66	2
C10		67.88	72.22	69.25	68		
P	C50	71.60	78.70	74.28	62	61	2
C27		69.15	78.30	72.91	59		
C20	C75	71.20	75.07	72.81	58	61	2
C3		68.10	72.84	69.84	63		
C24	C100	67.40	73.28	69.89	58	57	0
C28		126.43	132.37	128.98	57		

[1] Standard deviation.

Table C.16. Organic matter (OM) content of the reactors at day 10 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
C16	C0	67.13	70.25	68.35	61	60	1
C26		68.84	72.28	70.23	60		
P	C10	71.60	77.30	74.00	58	57	1
C10		67.88	74.84	70.99	55		
J	C20	70.64	75.15	72.12	67	65	2
C9		71.17	74.85	72.54	63		
C30	C30	115.48	119.56	116.92	65	65	0
E1		114.78	119.00	116.28	64		
E29	C40	113.57	124.00	118.13	56	57	1
E28		113.27	124.01	117.83	58		
E39	C50	111.62	119.90	115.21	57	59	2
C22		125.44	133.54	128.57	61		
E35	C75	122.70	131.26	126.05	61	62	2
C28		126.44	137.70	130.49	64		
E23	C100	113.24	121.32	116.82	56	55	0
C25		69.64	76.64	72.78	55		

[1] Standard deviation.

Table C.17. Organic matter (OM) content of the reactors at day 13 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
e23	C0	113.26	117.15	114.82	60	61	1
c22		125.46	128.29	126.55	61		
c30	C10	115.51	127.90	120.85	57	57	0
e29		113.57	123.94	118.12	56		
e28	C20	113.28	118.96	115.58	60	63	3
e39		111.64	115.47	112.93	66		
p	C30	71.60	78.72	74.76	56	58	2
c24		67.41	71.63	69.10	60		
k	C40	66.81	77.42	71.22	58	56	3
c16		67.12	77.35	71.89	53		
c23	C50	69.37	82.33	75.39	54	52	1
c19		70.18	87.41	78.57	51		
c10	C75	67.95	77.73	71.94	59	61	2
c20		71.23	78.63	74.02	62		
e1	C100	114.78	139.47	127.08	50	52	2
e35		122.71	143.83	132.57	53		

[1] Standard deviation.

Table C.18. Organic matter (OM) content of the reactors at day 20 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
c16	C0	67.13	70.25	68.27	63	60	3
c23		69.37	71.94	70.47	57		
k	C10	66.81	73.02	69.92	50	55	5
c25		69.63	75.12	71.86	59		
c20	C20	71.20	76.73	73.70	55	57	2
J		70.62	75.48	72.65	58		
c24	C30	67.42	73.85	70.51	52	54	2
c3		68.09	74.39	70.81	57		
c19	C40	70.18	80.78	74.79	57	56	0
p		71.60	80.83	75.70	56		
c10	C50	67.89	76.98	72.43	50	54	4
c9		71.16	78.09	74.13	57		
c15	C75	67.78	74.81	71.18	52	55	4
c26		68.86	79.28	73.15	59		
c27	C100	69.15	73.78	71.21	56	53	2
e28		113.27	121.53	117.34	51		

[1] Standard deviation.

Table C.19. Organic matter (OM) content of the reactors at day 30 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
J	C0	70.62	75.92	73.27	50	54	4
C26		68.85	73.06	70.62	58		
C23	C10	69.37	79.36	73.83	55	54	1
C10		67.89	78.16	72.78	52		
C25	C20	69.64	74.71	71.91	55	54	1
C24		67.42	75.84	71.36	53		
C20	C30	71.20	77.83	74.23	54	52	3
C9		71.15	79.87	75.62	49		
C1	C40	67.87	78.66	73.44	48	47	0
C8		59.22	66.81	63.26	47		
K	C50	66.82	77.16	71.89	51	50	1
C3		68.10	77.21	72.72	49		
E30	C75	115.51	129.28	122.01	53	50	3
E35		122.71	139.24	131.47	47		
C19	C100	70.19	81.85	76.56	45	47	2
C16		67.13	78.14	72.77	49		

[1] Standard deviation.

Table C.20. Organic matter (OM) content of the reactors at day 65 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
UA009	C0	80.72	86.02	83.35	50	52	2
UA007		87.03	94.88	90.66	54		
UA008	C10	69.77	75.97	72.54	55	54	1
UA006		71.80	77.94	74.67	53		
UA012	C20	80.77	85.56	83.01	53	53	0
UA010		69.57	75.53	72.33	54		
C28	C30	126.45	133.18	129.87	49	51	2
E23		113.25	123.94	118.32	53		
UA015	C40	85.25	92.20	88.85	48	48	0
UA011		77.66	84.78	81.33	48		
E35	C50	122.71	134.91	129.55	44	46	2
E28		113.25	122.61	118.11	48		
C22	C75	125.45	132.57	129.12	48	49	1
E29		113.55	120.70	117.11	50		
E39	C100	111.63	118.36	115.12	48	48	0
UA013		78.25	83.58	81.06	47		

[1] Standard deviation.

Table C.21. Organic matter (OM) content of the reactors at day 100 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD[1]
C28	C0	126.44	142.23	134.32	50	50	0
E28		113.27	136.06	124.78	49		
E23	C10	113.24	129.69	121.32	51	51	0
E29		113.56	126.74	119.96	51		
E35	C20	122.71	150.34	136.84	49	48	2
C22		125.46	148.28	137.65	47		
UA14	C30	71.69	102.35	88.67	45	45	1
UA13		78.27	100.87	90.45	46		
UA10	C40	69.58	97.19	84.77	45	45	0
UA15		85.25	112.39	100.01	46		
UA11	C50	77.66	110.69	96.96	42	42	1
UA06		71.81	103.29	89.96	42		
UA07	C75	87.03	126.04	106.55	50	48	2
UA12		80.78	110.1	96.33	47		
UA09	C100	80.72	110.58	96.96	46	46	0
UA08		69.78	100.34	86.44	45		

[1] Standard deviation.

Table C.22. Summary of organic matter (OM) content of the reactors during composting.

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	78±1[1]	77±3	74±2	66±6	65±0	63±2	57±0	54±1
3	74±2	71±1	73±1	66±0	64±1	63±2	59±3	57±3
6	74±1	66±1	72±0	67±2	66±2	61±2	61±2	57±0
10	60±1	57±1	65±2	65±0	57±1	59±2	62±2	55±0
13	61±1	57±0	63±3	58±2	56±3	52±1	61±2	52±2
20	60±3	55±5	57±2	54±2	56±0	54±4	55±4	53±2
30	54±4	54±1	54±1	52±3	47±0	50±1	50±3	47±2
65	52±2	54±1	53±0	51±2	48±0	46±2	49±1	48±0
100	50±0	51±0	48±2	45±1	45±0	42±1	48±2	46±0

[1] Organic matter ± standard deviation.

Raw data to calculate relative organic matter removal (ROR) are presented in Table C23-C31.

Table C.23. Organic matter removal in C0 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm[3])	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	5460	0	-	46.86	77.74	-	-	-
3	4340	4810	600	55.43	48.51	73.88	212	212	106
6	3980	4840	1000	51.96	41.23	73.89	196	408	205
10	4350	4200	0	43.78	43.78	60.25	327	735	369
13	4140	3900	0	43.19	43.19	60.69	23	757	381
20	3600	3360	0	40.74	40.74	60.33	138	895	450
30	2940	2720	0	45.25	45.25	53.98	108	1003	504
65	1780	1900	350	65.80	53.68	56.07	8	1010	508
100	1320	-	-	77.90	-	49.80	60	1070	538

[1] Total solids, [2] Organic matter, [3] Dry matter,

[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).

[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.

[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.24. Organic matter removal in C10 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	5480	0	-	44.99	76.55	-	-	-
3	4720	6800	2200	50.12	33.91	71.11	205	205	109
6	6700	6500	0	31.88	31.88	65.62	238	443	235
10	6040	5830	0	32.42	32.42	56.61	251	694	368
13	5260	4960	0	31.69	31.69	56.51	128	822	436
20	3540	2960	0	39.98	39.98	54.65	115	937	496
30	2540	2360	0	43.41	43.41	53.87	53	990	524
65	1480	1600	350	64.73	50.57	54.29	32	1021	541
100	1040	-	-	78.16	-	51.16	23	1045	554

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.25. Organic matter removal in C20 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	6340	0	-	47.55	73.66	-	-	-
3	5240	5600	500	53.24	48.49	73.16	180	180	81
6	4180	4500	500	56.55	50.27	72.33	277	456	206
10	3980	3480	0	48.89	48.89	64.98	372	828	373
13	3380	3190	0	45.47	45.47	62.91	139	967	435
20	2900	2700	0	42.47	42.47	56.51	217	1183	533
30	2320	2120	0	46.58	46.58	54.22	62	1245	561
65	1360	1480	340	72.84	56.11	53.46	6	1251	563
100	1000	-	-	80.88	-	47.72	58	1309	590

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.26. Organic matter removal in C30 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	7860	0	-	46.77	65.84	-	-	-
3	7460	7670	400	44.78	42.44	66.36	204	204	84
6	5380	5090	0	51.95	51.95	66.50	301	505	209
10	4680	4440	0	51.78	51.78	64.58	193	699	289
13	4180	3980	0	48.65	48.65	57.79	310	1008	417
20	3660	3500	0	46.06	46.06	54.38	202	1210	500
30	2840	2680	0	48.36	48.36	51.52	169	1380	570
65	1900	2000	340	68.52	56.88	50.88	5	1385	572
100	1470	-	-	77.41	-	45.36	63	1447	598

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.27. Organic matter removal in C40 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	10280	0	-	44.90	64.97	-	-	-
3	8600	8500	0	44.81	44.81	63.93	536	536	179
6	7420	7400	200	47.87	46.58	65.93	93	628	210
10	6620	6440	0	51.40	51.40	56.91	336	964	322
13	6280	6020	0	44.88	44.88	55.90	308	1273	424
20	5340	5040	0	46.46	46.46	55.58	132	1404	468
30	4300	4100	0	47.65	47.65	46.77	343	1747	583
65	3100	3020	200	59.32	55.40	48.46	23	1770	590
100	2400	-	-	69.17	-	45.30	59	1829	610

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.28. Organic matter removal in C50 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	9740	0	-	44.46	63.45	-	-	-
3	8080	7900	0	48.41	48.41	63.46	266	266	97
6	6900	7800	1000	52.61	45.86	60.58	228	493	180
10	7320	7120	0	44.97	44.97	59.00	225	718	261
13	7160	6420	0	40.99	40.99	52.43	351	1069	389
20	6000	5540	0	38.80	38.80	53.60	132	1201	437
30	4880	4620	0	40.89	40.89	50.13	152	1353	492
65	3480	3300	0	53.16	53.16	46.01	96	1449	527
100	2420	-	-	68.93	-	41.96	107	1556	566

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.29. Organic matter removal in C75 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm^3)	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	11820	0	-	42.15	57.10	-	-	-
3	10460	10300	0	43.56	43.56	58.74	168	168	59
6	9080	8780	0	46.76	46.76	60.84	52	220	77
10	8780	8600	0	44.83	44.83	62.45	40	260	91
13	7740	7600	0	43.83	43.83	60.75	347	607	213
20	7380	6880	0	44.85	44.85	55.23	195	802	282
30	6120	5880	0	46.97	46.97	49.90	270	1072	377
65	4860	4600	80	52.87	51.95	49.33	111	1183	416
100	3900	-	-	59.64	-	48.46	52	1235	434

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

Table C.30. Organic matter removal in C100 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	OM[2] (%, dm[3])	OM$_{removed}$[4] (g)	Accumulated OM$_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	10440	0	-	41.10	53.67	-	0	0
3	9480	9250	0	41.70	41.70	56.60	65	65	28
6	8440	8840	600	45.31	42.24	57.36	0	65	28
10	8320	7900	0	43.85	43.85	55.42	120	185	80
13	7700	7140	0	45.01	45.01	51.75	126	311	135
20	6720	6260	0	43.56	43.56	53.12	108	419	182
30	5380	5100	0	45.83	45.83	47.07	288	707	307
65	4000	3800	120	56.60	54.82	47.71	20	727	316
100	2920	-	-	68.61	-	45.55	81	808	351

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*OM (at day 0)- Mass $_{out}$*TS$_{out}$*OM (at day 3).
[5] Accumulated OM$_{removed}$ at day 6= Accumulated OM $_{removed}$ at day 3+ OM $_{removed}$ at day 6.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated OM$_{removed}$ / OM added at day 0.

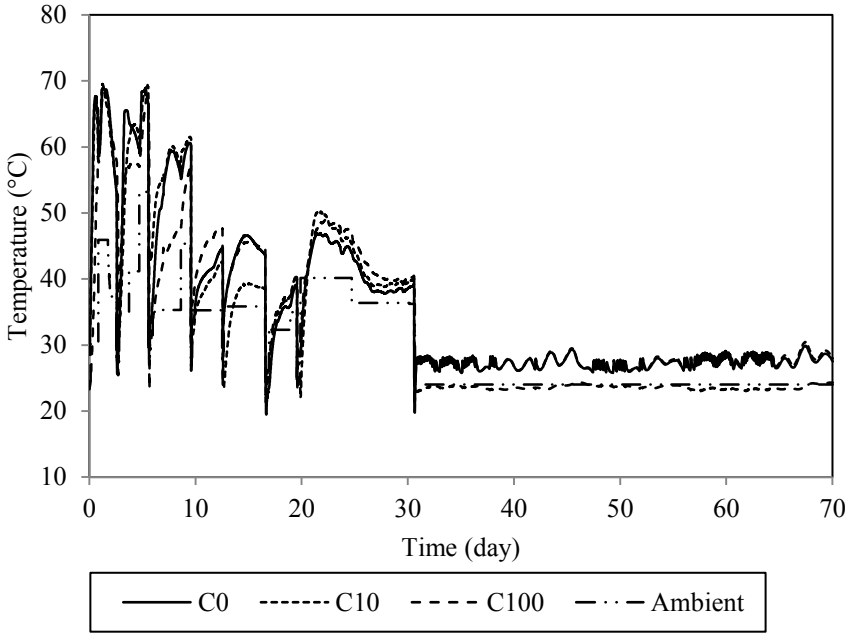
Table C.31. Summary of relative organic matter removal (ROR) during composting (g OM $_{removed}$. Kg^{-1} OM $_{added}$).

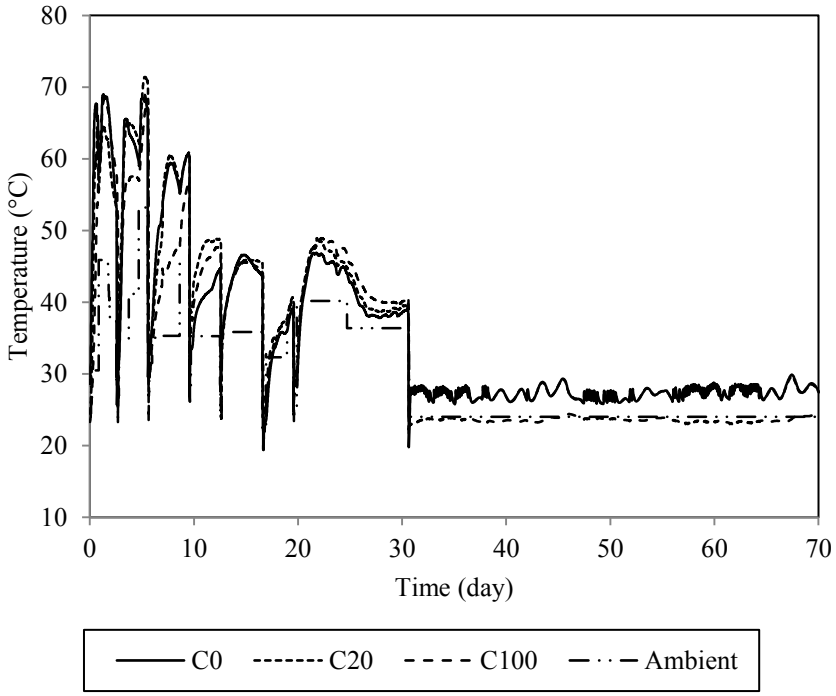
Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
3	106	109	81	84	179	97	59	28
6	205	235	206	209	210	180	77	35
10	369	368	373	289	322	261	91	87
13	381	436	435	417	424	389	213	142
20	450	496	533	500	468	437	282	189
30	504	524	561	570	583	492	377	314
65	508	541	563	572	590	527	416	323
100	538	554	590	598	610	566	434	358

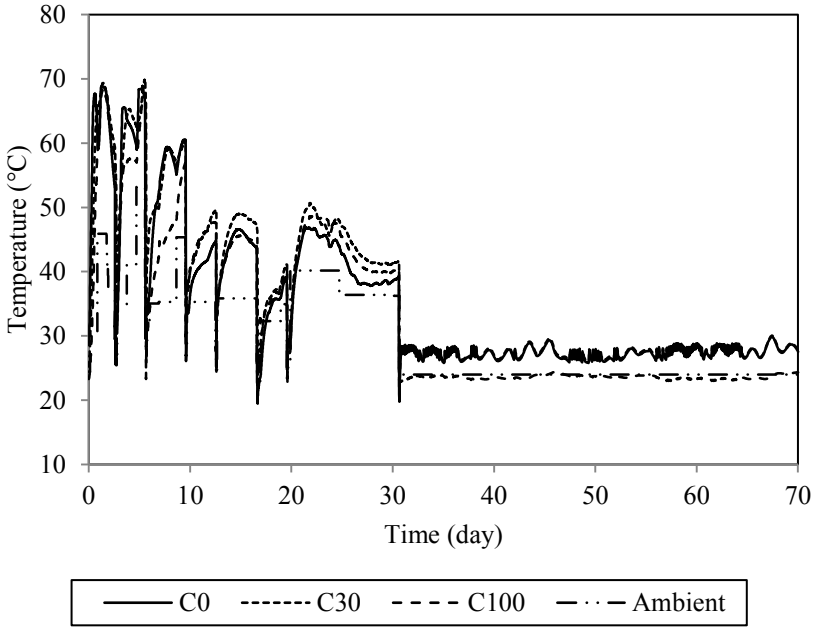
Due to the large volume, the original temperature profiles data and relative heat generation (RHG) calculated from temperature data cannot be presented in the Appendix in their original form. However, the data can be reached from the following link;

http://goo.gl/lTPQSs

Temperature and RHG profile for each reactor during composting are presented in Figure C7 and C8, respectively.




80
70
60
50
40
30
20
10
Temperature (°C)
0
10
20
30
40
50
60
70
Time (day)
C0
C20
C100
Ambient


80
70
60
50
40
30
20
10
Temperature (°C)
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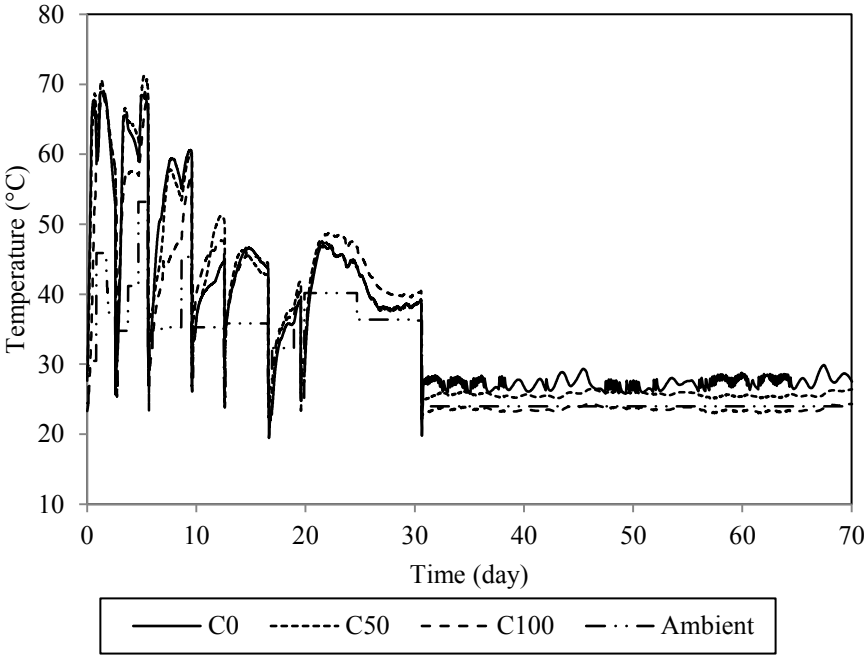
10
20
30
40
50
60
70
Time (day)
C0
C30
C100
Ambient



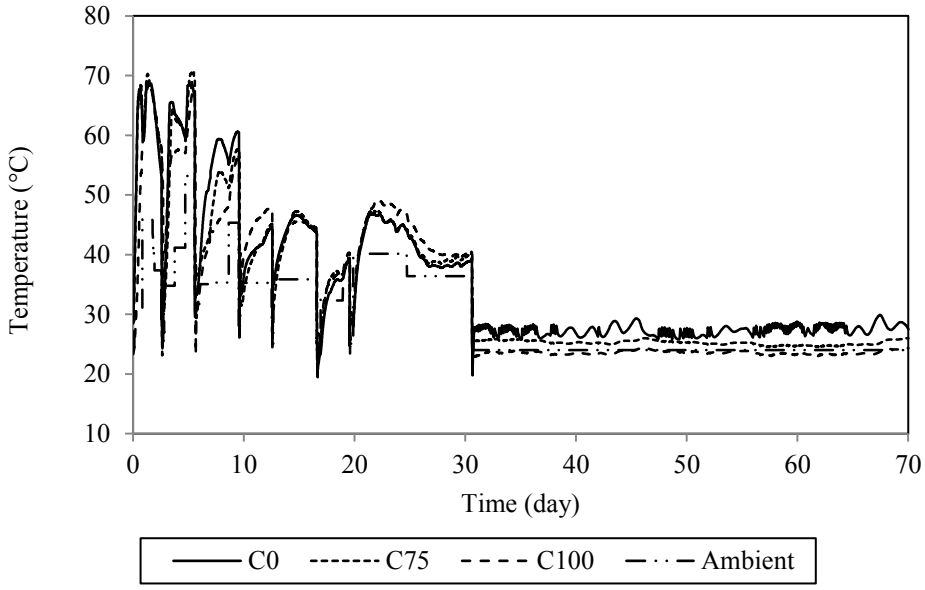
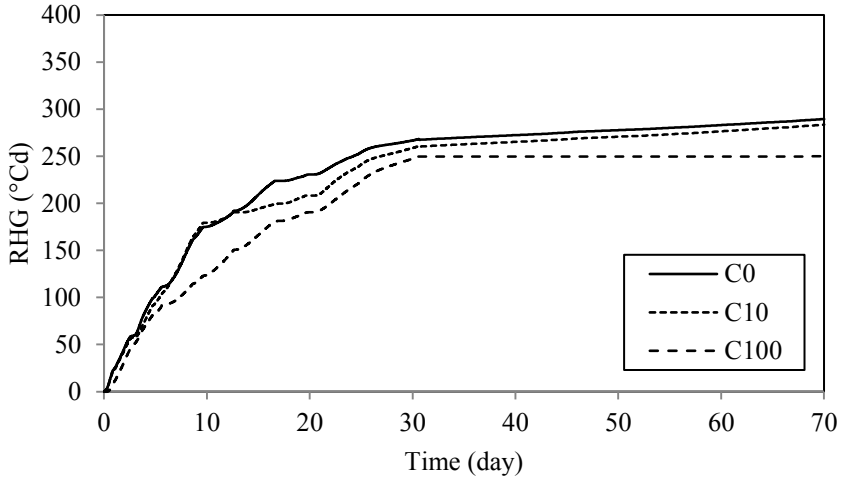
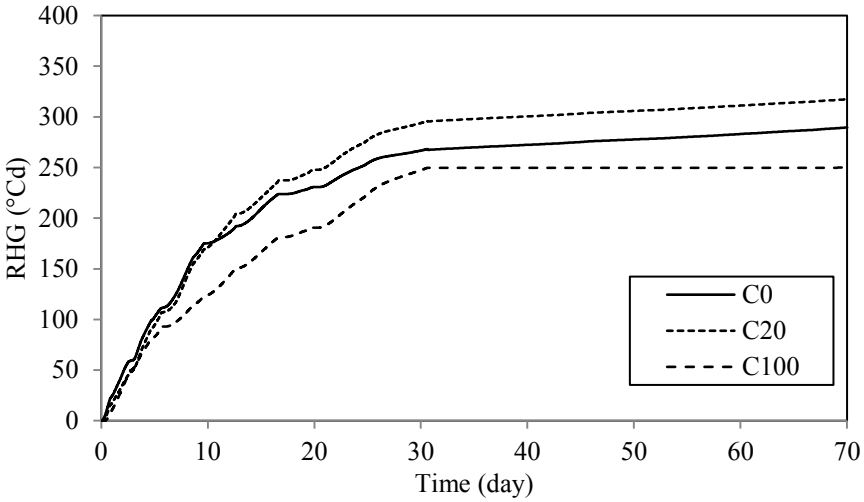
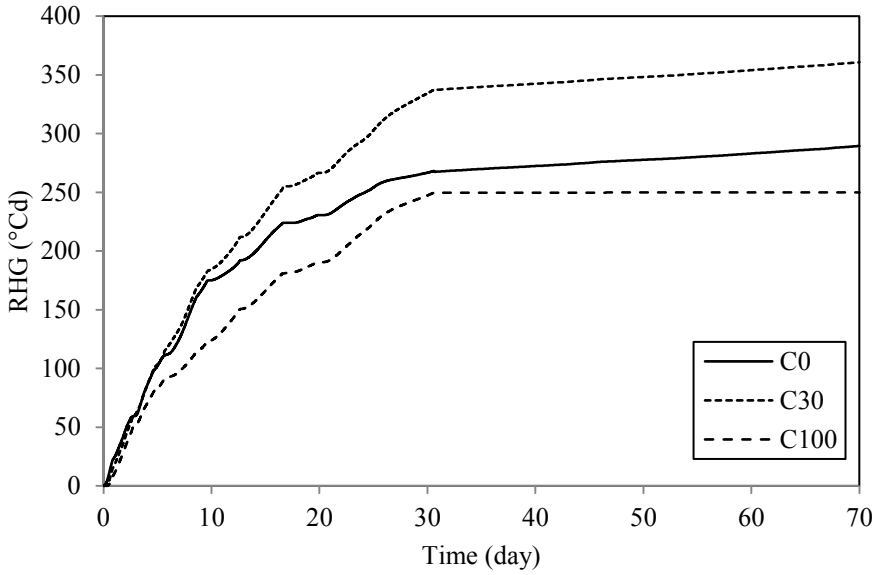


Figure C7. Temperature profile during composting.


400
350
300
250
200
150
100
50
0
RHG (°Cd)
0
10
20
30
40
50
60
70
Time (day)
C0
C10
C100


400
350
300
250
200
150
100
50
0
RHG (°Cd)
0
10
20
30
40
50
60
70
Time (day)
C0
C20
C100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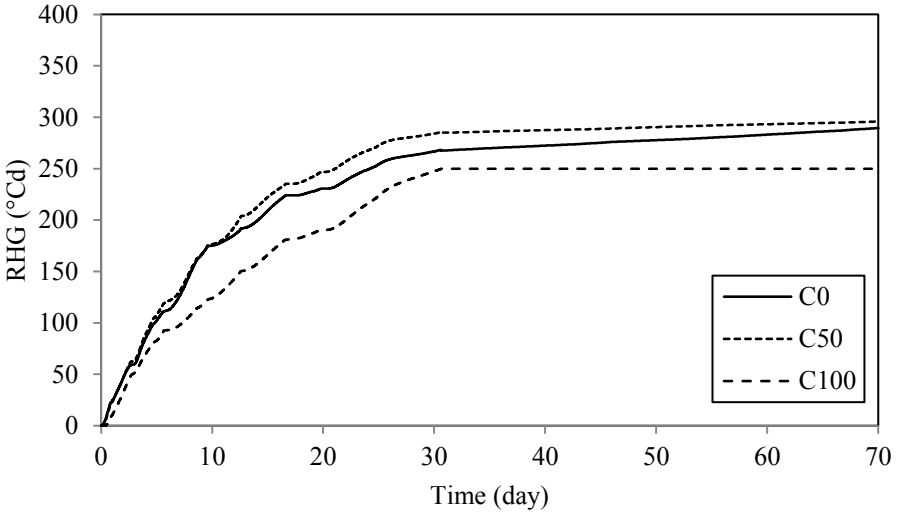
350
300
250
200
150
100
50
0
RHG (°Cd)
0
10
20
30
40
50
60
70
Time (day)
C0
C30
C100


400
350
300
250
200
150
100
50
0
RHG (°Cd)
0
10
20
30
40
50
60
70
Time (day)
C0
C50
C100

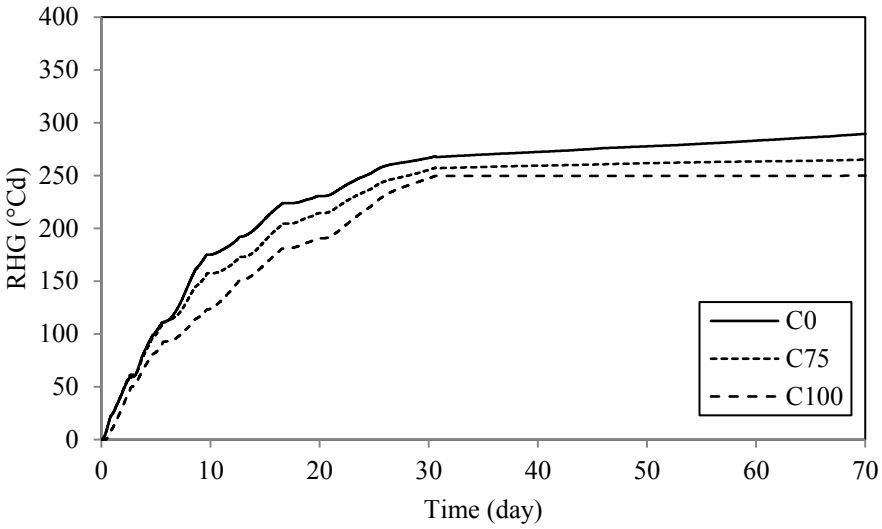


Figure C.8. Relative heat generation (RHG) profile during composting.

Respirometry test

Respirometry test was conducted using ER-10, a multi gas respirometer designed to detect small volumes of gas consumption or generation. It was equipped with two gas sensors: O_2 and CO_2. The following information was adapted from Oxymax ER user manual, Columbus Instruments.

ER-10 finds many applications in biology: bacterial and microbial respiration, insects, plants, food, and chemical oxidation. It is a highly automated system that performs the many tasks that might otherwise be performed manually in making respirometric assessment. Among these automated tasks are volume measurement, sample chamber refreshing and the sequential indexing of the gas sensors across multiple chambers. ER-10 can scan a maximum of ten test chambers. ER-10 performs measurements in a closed gas sensing loop. During measurement, the headspace content of the test chamber is circulated through the sensor and back to the test chamber for a fixed period of time. ER-10 takes a series of gas measurements, recording the net increase or decrease in the concentration of the monitored gas over the fixed period. The change in gas concentration, along with knowledge of the working volumes (headspace volume and gas sensing loop volume), allows ER-10 to compute the volume of gas consumed or produced by sample in the test chamber. Upon completion of one measurement cycle ER-10 advances to the next test chamber and repeats the process. ER-10 maintains the headspace composition of test chambers that are not undergoing measurement by continuous ventilation with either ambient air or from a source of user supplied gas.

Consumption and production information is normalized by ER-10 to STP: 0° C, 760 mmHg. Results may be presented in microliters (ul), milliliters (ml), micrograms (mg) or milligrams (mg) per hour or minute. Gas measurement is performed with a dedicated gas sensor. Measurements are not made by any indirect means that might otherwise be subject to error associated with temperature and pressure change as found with manometric or electrolytic respirometers. ER-10 communicates with a host microcomputer for the purpose of control, data collection and presentation. Software supplied with the system allows the user to configure the system for use with a wide variety of test samples. Included are routines for computer-based gas sensor calibration and measurement of test chamber headspace volume and various diagnostics. Sensors employed by ER-10 vary in their method of detection according to the most effective method for sensing a particular gas. Carbon dioxide, carbon monoxide and methane are sensed

by a single-beam, non-dispersive IR spectrophotometer. All other, non-hydrocarbon gases, are sensed by electro-chemical means. Carbon dioxide and oxygen are the two most common gases sensed by ER-10. The CO_2 sensor has a working range of 0-0.9% and the oxygen sensor's range is 19 – 21%. Expanded ranges are available as an option for both CO_2 and O_2. Other gas sensors: H_2, CH_4, CO, H_2S and SO_2 are available. ER-10 is intended for use with computers that are compatible with the IBM-PC/XT/AT (286, 386, 486 and Pentium class processors) standard. ER-10 is provided with a WINDOWS 95/98 compatible program.

The respirometry test results achieved by running ER-10 during composting are presented in Table C32-C41.

Table C.32. Specific oxygen uptake rate (SOUR) at day 0 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	1299.34	1137.27	1192.90	1218.31	1157.96	1586.70	1105.17	820.31
2	1138.83	1098.28	1271.35	1291.83	1183.57	1415.76	1004.81	742.08
3	1100.06	1061.95	1245.28	1270.37	1140.45	1320.74	986.86	751.44
4	1061.81	1062.54	1146.47	1216.88	1162.99	1273.23	982.14	789.49
5	1067.75	1130.77	1163.85	1193.99	1179.41	1185.43	898.78	756.33
6	1130.82	1088.83	1107.74	1267.22	1126.45	1152.12	857.69	794.16
7	975.74	1069.04	1126.86	1202.00	1099.09	1127.44	790.15	755.05
8	1288.75	1096.51	1172.04	1202.86	1137.39	1094.13	808.10	698.08
9	1157.44	1127.23	1109.98	1111.90	1094.93	1015.42	773.39	747.61
10	1266.52	1077.60	1184.95	1174.54	1138.05	986.07	726.39	717.00
11	1221.03	1049.54	1051.14	1190.28	1150.08	966.74	634.29	711.47
12	1294.95	1051.02	1109.73	1111.04	1170.44	1003.54	516.46	516.76
13	1193.37	1086.46	1065.04	1153.37	1065.39	728.49	825.10	753.14
14	1285.13	1129.59	933.71	1047.25	1261.04	1116.72	805.50	720.83
15	1309.17	1081.15	1008.69	1162.81	1188.82	1034.51	747.17	726.99
Average	1186.05	1089.85	1125.98	1187.64	1150.40	1133.80	830.80	733.38

Table C.33. Specific oxygen uptake rate (SOUR) at day 3 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	1142.82	1062.82	1039.04	1026.39	1000.01	912.79	945.97	992.66
2	1254.47	1078.02	1022.28	1092.88	947.80	930.61	910.03	887.18
3	1176.16	1044.81	1106.90	1098.33	960.68	910.47	1046.64	892.32
4	1147.35	1087.17	1142.42	1139.48	971.56	934.08	1080.66	864.17
5	1093.94	1020.16	1134.04	1110.63	1000.70	922.93	939.69	812.54
6	1021.09	987.54	1101.63	1099.14	990.88	945.89	1020.47	824.80
7	982.19	978.69	1067.94	1102.81	992.51	952.56	946.50	867.79
8	923.44	969.83	1082.31	1077.68	982.91	964.87	951.56	868.14
9	893.08	913.16	1093.96	1100.22	1002.12	983.05	921.90	885.78
10	832.16	797.89	1072.41	1106.31	999.59	938.50	994.13	928.06
11	836.07	916.99	1048.22	1092.83	1006.98	937.42	953.48	907.39
12	790.38	875.82	1078.96	1089.92	1161.13	899.82	991.16	896.06
13	818.68	913.16	1057.72	1100.11	1043.46	964.94	910.21	896.53
14	797.90	837.29	1048.86	1070.07	1057.39	937.13	815.64	940.80
15	802.32	796.12	1073.45	1052.71	1021.65	945.60	790.70	961.12
Average	967.47	951.96	1078.01	1090.63	1009.29	938.71	947.92	895.02

Table C.34. Specific oxygen uptake rate (SOUR) at day 6 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	866.37	863.62	440.15	752.38	1085.66	656.44	692.89	710.66
2	724.52	634.93	534.07	812.56	1086.91	673.79	776.70	782.95
3	654.16	709.88	386.92	698.19	996.55	678.84	655.54	684.20
4	830.26	733.34	438.86	631.71	875.74	635.72	645.24	761.33
5	807.55	828.95	421.11	685.27	795.10	677.88	643.19	776.82
6	743.51	685.36	521.95	543.49	847.19	702.45	784.35	846.86
7	645.22	650.69	344.07	784.83	689.99	686.79	761.12	779.73
8	723.78	787.27	225.49	712.68	611.55	625.85	754.65	636.11
9	697.72	635.28	360.52	750.18	610.92	555.99	791.12	686.13
10	721.17	724.94	407.26	638.01	537.81	658.37	673.48	684.84
11	838.45	750.85	385.62	789.56	591.46	617.90	824.05	697.11
12	755.80	654.19	337.15	592.64	584.87	657.40	859.64	666.77
13	803.08	635.98	366.58	727.81	528.40	649.21	727.89	549.62
14	748.35	691.67	316.81	632.66	538.75	681.25	741.71	611.58
15	661.23	624.08	294.73	711.42	519.61	717.15	692.59	634.82
Average	747.63	707.16	384.68	697.66	727.33	658.04	734.87	701.00

Table C.35. Specific oxygen uptake rate (SOUR) at day 10 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	947.81	681.73	712.89	614.30	539.02	803.95	1029.93	691.56
2	690.43	759.64	923.14	692.76	617.62	716.28	1176.36	613.31
3	627.77	796.30	659.39	595.93	409.13	898.11	743.80	495.13
4	475.02	497.83	893.58	564.16	405.39	652.64	673.96	457.64
5	1052.44	347.74	586.64	546.94	376.56	637.05	494.44	661.40
6	621.06	678.29	597.44	745.19	470.52	532.50	634.13	503.69
7	795.06	624.44	489.96	723.38	382.18	750.05	505.47	623.50
8	575.18	167.28	728.85	746.34	509.82	624.72	617.59	537.92
9	748.06	938.38	631.70	672.47	361.22	401.32	673.96	731.90
10	633.36	832.97	696.93	715.72	549.12	535.75	567.35	566.86
11	614.34	879.37	580.54	638.41	402.39	949.41	478.51	663.85
12	458.80	678.29	751.37	713.43	510.19	729.27	635.36	553.41
13	947.25	415.91	652.82	638.03	439.82	579.91	379.25	665.07
14	506.36	422.79	591.81	900.97	410.25	447.43	607.79	516.73
15	477.82	781.98	518.12	863.84	423.35	559.78	550.81	528.96
Average	678.05	633.53	667.68	691.46	453.77	654.54	651.25	587.40

Table C.36. Specific oxygen uptake rate (SOUR) at day 13 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	638.94	655.31	583.20	610.02	611.90	605.18	616.61	598.82
2	605.34	632.25	611.76	585.75	640.55	572.76	661.21	600.62
3	629.34	642.30	577.80	586.89	592.39	600.67	603.17	584.07
4	671.62	610.67	563.23	572.90	547.73	577.58	649.42	574.21
5	633.38	615.20	569.12	561.13	571.70	575.81	632.98	601.56
6	678.10	604.00	531.72	603.24	625.41	579.61	655.35	588.89
7	613.68	642.30	605.62	569.34	619.77	598.01	643.26	613.14
8	656.71	611.00	596.13	636.50	587.25	573.33	668.94	610.77
9	668.00	619.57	613.40	638.64	603.35	594.90	676.00	624.80
10	673.47	613.64	592.77	568.27	562.10	564.64	641.84	588.68
11	627.91	630.11	529.02	590.03	581.67	540.15	672.10	613.72
12	652.75	599.80	527.71	623.15	580.37	524.55	612.33	612.93
13	628.67	619.07	596.78	614.16	609.98	526.83	651.90	611.06
14	621.68	675.07	543.75	599.88	564.14	616.02	599.94	608.68
15	665.39	635.79	572.72	593.82	600.01	564.32	622.01	591.48
Average	644.33	627.07	574.31	596.91	593.22	574.29	640.47	601.56

Table C.37. Specific oxygen uptake rate (SOUR) at day 20 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	501.16	488.43	498.06	492.85	420.12	545.01	515.74	492.09
2	548.84	515.93	507.83	477.78	434.57	544.08	507.33	519.90
3	515.67	488.84	486.16	447.28	406.68	561.32	519.48	486.83
4	538.16	524.10	519.73	441.40	427.94	554.89	536.48	484.89
5	545.42	509.14	542.46	462.57	437.89	561.23	550.50	500.45
6	540.87	517.10	503.21	457.69	425.09	594.78	524.50	487.16
7	585.42	495.49	536.25	471.25	433.92	523.67	544.08	503.95
8	472.55	470.94	457.49	418.01	387.49	540.82	507.10	460.39
9	462.87	512.50	464.09	439.68	408.22	564.95	528.30	483.85
10	539.59	471.42	497.13	443.77	420.24	531.50	502.30	489.17
11	485.64	463.12	435.15	434.65	378.96	504.00	476.42	486.19
12	417.89	465.38	413.35	398.99	375.94	500.28	478.47	452.74
13	490.91	441.86	454.98	423.53	406.79	513.79	470.41	472.12
14	427.71	455.78	388.24	405.45	398.38	514.63	479.11	453.13
15	501.01	431.16	446.25	421.09	401.17	544.45	476.95	468.10
Average	504.91	483.41	476.69	442.40	410.89	539.96	507.81	482.73

Table C.38. Specific oxygen uptake rate (SOUR) at day 30 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	452.15	431.90	392.00	374.74	337.31	417.53	361.99	406.54
2	399.39	409.95	346.10	328.22	287.25	400.68	338.45	392.38
3	490.88	411.09	394.39	354.72	341.54	436.59	376.00	442.74
4	434.65	382.51	341.94	302.27	332.48	427.10	381.69	395.53
5	393.35	390.77	327.01	306.15	311.69	422.67	327.85	405.78
6	403.51	384.08	352.44	328.78	310.13	406.38	356.08	372.74
7	373.66	361.70	332.33	312.00	306.04	422.59	325.79	396.47
8	411.36	420.78	328.17	320.63	306.27	411.91	336.95	374.45
9	397.46	450.43	314.94	288.43	271.66	422.28	312.56	389.56
10	434.52	415.58	338.53	325.22	319.56	422.59	371.80	401.42
11	439.28	420.71	356.94	332.26	358.25	491.88	402.95	417.30
12	398.11	384.43	317.87	298.16	304.19	418.72	360.71	382.13
13	416.51	370.04	331.71	306.23	319.78	440.94	346.91	391.01
14	370.44	393.34	355.17	307.02	292.23	425.04	350.18	368.39
15	413.03	422.42	334.10	317.31	301.51	419.19	351.53	366.43
Average	415.22	403.31	344.24	320.14	313.33	425.74	353.43	393.53

Table C.39. Specific oxygen uptake rate (SOUR) at day 65 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	301.45	360.12	353.44	293.53	300.61	326.53	272.40	351.63
2	307.92	372.63	378.80	292.22	297.26	311.59	266.21	298.85
3	315.44	292.64	327.91	270.88	279.68	285.58	270.90	295.54
4	311.53	332.85	311.32	291.39	285.36	321.64	271.61	320.66
5	270.44	288.73	282.35	262.46	308.47	318.84	277.13	283.61
6	301.37	308.38	270.33	272.13	310.22	314.17	259.27	309.88
7	304.23	299.96	266.04	272.96	281.86	308.07	258.13	304.76
8	253.21	269.02	223.32	250.01	293.01	289.03	288.98	279.52
9	281.81	299.29	243.88	255.88	279.68	317.48	260.59	299.64
10	211.07	263.29	216.59	242.96	255.46	276.45	292.36	244.22
11	120.02	177.93	159.21	119.76	168.41	145.63	277.75	160.54
12	189.18	224.85	195.87	200.15	228.75	231.77	296.09	225.06
13	199.64	254.87	212.34	221.73	233.74	249.01	278.28	224.88
14	225.82	268.47	203.61	228.91	258.60	258.57	280.21	272.53
15	210.02	230.70	178.48	217.11	226.31	211.94	277.31	229.16
Average	253.54	282.91	254.90	246.14	267.16	277.75	275.15	273.37

Table C.40. Specific oxygen uptake rate (SOUR) at day 100 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C10	C20	C30	C40	C50	C75	C100
1	305.38	265.79	287.55	259.07	269.54	296.86	265.51	290.93
2	277.84	367.33	310.82	260.95	252.54	289.74	256.61	278.14
3	241.71	314.40	250.97	243.90	235.71	257.21	242.63	242.93
4	226.55	302.31	242.46	234.91	255.56	258.22	238.31	249.57
5	260.72	301.00	251.13	236.46	310.75	283.13	252.80	252.25
6	243.60	281.46	246.44	225.53	322.27	284.72	274.97	249.82
7	246.58	273.30	249.28	230.15	259.75	343.81	270.84	300.80
8	251.79	298.13	205.89	249.79	229.67	324.69	336.93	266.45
9	204.63	238.34	221.04	246.73	235.76	304.73	249.17	284.29
10	239.20	242.22	289.18	235.42	279.83	289.04	263.15	261.94
11	190.89	256.02	249.71	243.71	230.67	243.10	223.82	258.77
12	186.15	249.07	236.80	241.26	236.27	232.87	222.04	206.63
13	309.37	262.11	211.45	199.82	215.35	211.84	206.79	176.90
14	190.82	252.29	182.78	188.47	246.50	233.63	225.15	183.05
15	193.66	204.24	189.81	159.98	201.04	207.65	209.07	153.26
Average	237.93	273.87	241.69	230.41	252.08	270.75	249.19	243.72

Table C.41. Summary of specific oxygen uptake rate (SOUR) during composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	1,186	1,090	1,126	1,188	1,150	1,134	831	733
3	967	952	1078	1091	1009	939	948	895
6	748	707	385	698	727	658	735	701
10	678	634	668	691	454	655	651	587
13	644	627	574	597	593	574	640	602
20	505	483	477	442	411	540	508	483
30	415	403	344	320	313	426	353	394
65	254	283	255	246	267	278	275	273
100	238	274	242	230	252	271	249	244

C:N ratio test raw data are presented in Table C42-C47.

Table C.42. Carbon content changes during composting (% dry matter).

	Day								
Reactor	0	3	6	10	13	20	30	65	100
C0-1	36.5	34.5	33.6	35.2	31.7	29.2	26.4	24.7	25.8
C0-2	35.5	34.1	33.3	29.0	32.4	28.6	24.8	26.1	25.2
C10-1	36.3	36.3	29.9	30.0	28.0	28.4	27.0	25.0	25.5
C10-2	36.3	31.3	29.4	28.6	28.5	27.1	27.2	23.6	24.9
C20-1	36.6	32.4	28.0	29.7	29.8	28.4	24.4	27.1	26.5
C20-2	37.5	32.4	30.4	32.3	27.3	28.9	26.7	27.9	27.7
C30-1	36.6	32.0	32.8	29.3	28.6	29.1	26.5	25.8	23.9
C30-2	38.5	30.8	28.5	30.1	27.7	26.7	26.0	26.2	25.0
C40-1	36.3	31.7	30.5	28.4	27.1	26.8	23.7	23.7	23.1
C40-2	34.6	30.5	30.9	28.2	27.3	26.3	22.5	24.0	21.5
C50-1	33.0	31.0	28.9	28.4	26.7	26.4	25.2	23.4	23.3
C50-2	33.6	29.2	29.9	28.3	28.0	27.6	21.8	23.0	21.3
C75-1	33.5	32.2	28.7	25.5	25.8	26.8	23.5	24.0	22.7
C75-2	33.1	28.9	26.9	26.9	26.6	24.6	24.3	22.8	22.2
C100-1	26.3	23.6	22.7	24.0	22.7	22.2	21.0	21.2	21.6
C100-2	22.7	23.9	23.7	20.4	21.6	22.4	22.8	22.0	21.3

Table C.43. Summary of carbon content changes during composting (% dry matter).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	36.0±0.5[1]	36.3±0.0	37.1±0.4	37.6±0.9	35.5±0.8	33.3±0.3	33.3±0.2	24.5±1.8
3	34.3±0.2	33.8±2.5	32.4±0.0	31.4±0.6	31.1±0.6	30.1±0.9	30.6±1.7	23.8±0.1
6	33.5±0.2	29.7±0.3	29.2±1.2	30.7±2.2	30.7±0.2	29.4±0.5	27.8±0.9	23.2±0.5
10	32.1±3.1	29.3±0.7	31.0±1.3	29.7±0.4	28.3±0.1	28.4±0.0	26.2±0.7	22.2±1.8
13	32.1±0.4	28.3±0.3	28.6±1.3	28.2±0.5	27.2±0.1	27.4±0.7	26.2±0.4	22.2±0.5
20	28.9±0.3	27.8±0.6	28.7±0.3	27.9±1.2	26.6±0.3	27.0±0.6	25.7±1.1	22.3±0.1
30	25.6±0.8	27.1±0.1	25.6±1.2	26.3±0.3	23.1±0.6	23.5±1.7	23.9±0.4	21.9±0.9
65	25.4±0.7	24.3±0.7	27.5±0.4	26.0±0.2	23.9±0.2	23.2±0.2	23.4±0.6	21.6±0.4
100	25.5±0.3	25.2±0.3	27.1±0.6	24.5±0.6	22.3±0.8	22.3±1.0	22.5±0.3	21.5±0.2

[1] Carbon content ± standard deviation.

Table C.44. Nitrogen content changes during composting (% dry matter).

	Day								
Reactor	0	3	6	10	13	20	30	65	100
C0-1	1.5	2.2	1.9	2.2	2.2	2.5	2.3	2.4	2.5
C0-2	1.4	2.0	1.8	2.1	2.2	2.4	2.2	2.5	2.4
C10-1	1.6	1.7	1.7	2.1	1.9	2.2	2.2	2.0	2.3
C10-2	1.5	1.7	1.6	1.8	2.0	2.1	2.3	2.0	2.2
C20-1	1.6	2.0	1.9	2.1	2.2	2.3	2.3	2.6	2.5
C20-2	1.7	1.7	1.8	1.9	2.1	2.5	2.3	2.6	2.6
C30-1	1.6	1.6	1.9	2.0	2.0	2.6	2.3	2.6	2.4
C30-2	1.8	1.9	1.3	2.2	2.0	2.2	2.5	2.7	2.6
C40-1	1.6	2.1	2.0	2.2	1.4	2.1	2.1	2.1	2.3
C40-2	1.7	2.1	2.0	2.2	2.0	2.1	1.9	2.3	2.2
C50-1	1.5	1.9	1.9	2.4	1.9	1.9	2.2	2.3	2.2
C50-2	1.7	1.9	1.9	2.5	1.8	2.1	2.0	2.2	2.1
C75-1	1.8	1.8	1.8	1.8	1.7	2.0	2.0	2.3	2.2
C75-2	1.9	1.7	1.7	1.9	1.7	1.8	2.1	2.2	2.2
C100-1	1.7	1.4	1.5	1.5	1.2	1.5	1.9	2.2	1.9
C100-2	1.5	1.4	1.6	1.3	1.5	1.4	1.9	2.0	1.9

Table C.45. Summary of nitrogen content changes during composting (% dry matter).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	1.4±0.1[1]	1.5±0.0	1.6±0.1	1.7±0.1	1.6±0.1	1.6±0.1	1.8±0.0	1.6±0.1
3	2.1±0.1	1.7±0.0	1.8±0.1	1.8±0.2	2.1±0.0	1.9±0.0	1.8±0.0	1.4±0.0
6	1.9±0.1	1.6±0.0	1.8±0.0	1.6±0.3	2.0±0.0	1.9±0.0	1.7±0.0	1.5±0.0
10	2.2±0.1	2.0±0.2	2.0±0.1	2.1±0.1	2.2±0.0	2.4±0.0	1.8±0.1	1.4±0.1
13	2.2±0.0	1.9±0.0	2.1±0.1	2.0±0.0	1.7±0.3	1.9±0.1	1.7±0.0	1.3±0.1
20	2.4±0.1	2.2±0.0	2.4±0.1	2.4±0.2	2.1±0.0	2.0±0.1	1.9±0.1	1.5±0.0
30	2.2±0.0	2.2±0.1	2.3±0.0	2.4±0.1	2.0±0.1	2.1±0.1	2.1±0.0	1.9±0.0
65	2.4±0.1	2.0±0.0	2.6±0.0	2.6±0.1	2.2±0.1	2.3±0.0	2.3±0.0	2.1±0.1
100	2.5±0.1	2.3±0.1	2.5±0.0	2.5±0.1	2.3±0.1	2.2±0.0	2.2±0.0	1.9±0.0

[1] Nitrogen content ± standard deviation.

Table C.46. C:N ratio changes during composting (% dry matter)[1].

	Day								
Reactor	0	3	6	10	13	20	30	65	100
C0-1	24.1	15.8	17.3	15.8	14.3	11.6	11.7	10.4	10.2
C0-2	26.1	16.6	18.2	13.8	14.7	12.0	11.4	10.4	11.1
C10-1	23.2	21.6	18.1	14.0	14.5	13.0	12.4	12.4	11.0
C10-2	24.2	18.5	18.3	16.0	14.5	12.8	11.9	11.7	11.3
C20-1	23.6	16.4	14.8	13.9	13.4	12.1	10.8	10.4	10.7
C20-2	22.5	19.0	16.9	17.0	13.2	11.8	11.6	10.6	10.8
C30-1	23.3	20.3	17.0	14.8	14.4	11.2	11.4	10.0	10.0
C30-2	21.9	16.0	22.1	13.6	13.6	12.0	10.3	9.7	9.8
C40-1	23.3	14.7	15.2	13.1	19.7	12.6	11.1	11.5	9.8
C40-2	20.8	14.9	15.2	12.7	13.8	12.3	11.6	10.6	9.7
C50-1	22.6	16.0	15.5	11.8	13.8	13.9	11.7	10.2	10.5
C50-2	20.0	15.3	15.4	11.5	15.5	13.2	10.8	10.4	10.5
C75-1	18.5	18.1	16.2	14.5	15.3	13.4	11.6	10.5	10.1
C75-2	17.7	16.6	15.8	14.1	15.4	13.8	11.6	10.3	10.2
C100-1	15.5	16.9	15.1	16.5	18.6	14.4	10.9	9.6	11.1
C100-2	15.2	17.6	15.1	16.0	14.6	15.5	11.8	11.0	11.0

[1] All C:N ratio values were calculated based on two decimal places of carbon and nitrogen values.

Table C.47. Summary of C:N ratio changes during composting (% dry matter).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	25.1±1.0[1]	23.7±0.5	23.0±0.6	22.6±0.7	22.0±1.3	21.3±1.3	18.1±0.4	15.4±0.1
3	16.2±0.4	20.0±1.5	17.7±1.3	18.1±2.1	14.8±0.1	15.7±0.4	17.3±0.8	17.2±0.3
6	17.7±0.4	18.2±0.1	15.8±1.0	19.5±2.5	15.2±0.0	15.5±0.1	16.0±0.2	15.1±0.0
10	14.8±1.0	15.0±1.0	15.4±1.6	14.2±0.6	12.9±0.2	11.7±0.1	14.3±0.2	16.3±0.2
13	14.5±0.2	14.5±0.0	13.3±0.1	14.0±0.4	16.8±3.0	14.6±0.8	15.3±0.1	16.6±2.0
20	11.8±0.2	12.9±0.1	11.9±0.2	11.6±0.4	12.4±0.1	13.5±0.3	13.6±0.2	14.9±0.5
30	11.5±0.1	12.1±0.3	11.2±0.4	10.9±0.5	11.3±0.2	11.2±0.5	11.6±0.0	11.4±0.5
65	10.4±0.0	12.0±0.4	10.5±0.1	9.8±0.2	11.0±0.4	10.3±0.1	10.4±0.1	10.3±0.7
100	10.6±0.4	11.2±0.1	10.7±0.1	9.9±0.1	9.8±0.1	10.5±0.0	10.1±0.0	11.1±0.1

[1] C:N ratio ± standard deviation.

Raw data to calculate carbon removal are presented in Table C48-C58.

Table C.48. Carbon removal in C0 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1]$_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	5460	0	-	46.86	36.0	-	-	-
3	4340	4810	600	55.43	48.51	34.3	96	96	104
6	3980	4840	1000	51.96	41.23	33.5	108	204	221
10	4350	4200	0	43.78	43.78	32.1	57	261	283
13	4140	3900	0	43.19	43.19	32.1	16	277	301
20	3600	3360	0	40.74	40.74	28.9	117	394	428
30	2940	2720	0	45.25	45.25	25.6	55	449	487
65	1780	1900	350	65.80	53.68	25.4	18	466	506
100	1320	-	-	77.90	-	25.5	0	466	506

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.49. Carbon removal in C10 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1]$_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	5480	0	-	44.99	36.3	-	-	-
3	4720	6800	2200	50.12	33.91	33.8	95	95	106
6	6700	6500	0	31.88	31.88	29.7	145	240	268
10	6040	5830	0	32.42	32.42	29.3	42	282	315
13	5260	4960	0	31.69	31.69	28.3	82	364	407
20	3540	2960	0	39.98	39.98	27.8	51	415	464
30	2540	2360	0	43.41	43.41	27.1	30	446	498
65	1480	1600	350	64.73	50.57	24.3	45	490	548
100	1040	-	-	78.16	-	25.23	0	490	548

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.50. Carbon removal in C20 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	6340	0	-	47.55	37.1	-	-	-
3	5240	5600	500	53.24	48.49	32.4	215	215	192
6	4180	4500	500	56.55	50.27	29.2	190	404	361
10	3980	3480	0	48.89	48.89	31.0	57	461	413
13	3380	3190	0	45.47	45.47	28.6	88	549	491
20	2900	2700	0	42.47	42.47	28.7	61	611	546
30	2320	2120	0	46.58	46.58	25.6	52	663	593
65	1360	1480	340	72.84	56.11	27.5	0	663	593
100	1000	-	-	80.88	-	27.1	9	672	584

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.51. Carbon removal in C30 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	7860	0	-	46.77	37.6	-	-	-
3	7460	7670	400	44.78	42.44	31.4	333	333	241
6	5380	5090	0	51.95	51.95	30.7	166	499	361
10	4680	4440	0	51.78	51.78	29.7	91	590	427
13	4180	3980	0	48.65	48.65	28.2	109	699	506
20	3660	3500	0	46.06	46.06	27.9	76	775	560
30	2840	2680	0	48.36	48.36	26.3	89	863	625
65	1900	2000	340	68.52	56.88	26.0	3	866	626
100	1470	-	-	77.41	-	24.5	16	882	638

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.52. Carbon removal in C40 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	10280	0	-	44.90	35.5	-	-	-
3	8600	8500	0	44.81	44.81	31.1	440	440	269
6	7420	7400	200	47.87	46.58	30.7	94	534	326
10	6620	6440	0	51.40	51.40	28.3	95	629	384
13	6280	6020	0	44.88	44.88	27.2	170	799	488
20	5340	5040	0	46.46	46.46	26.6	75	874	534
30	4300	4100	0	47.65	47.65	23.1	150	1024	625
65	3100	3020	200	59.32	55.40	23.9	12	1036	632
100	2400	-	-	69.17	-	22.3	29	1065	650

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.53. Carbon removal in C50 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	9740	0	-	44.46	33.3	-	-	-
3	8080	7900	0	48.41	48.41	30.1	265	265	184
6	6900	7800	1000	52.61	45.86	29.4	84	349	242
10	7320	7120	0	44.97	44.97	28.4	117	466	323
13	7160	6420	0	40.99	40.99	27.4	105	571	396
20	6000	5540	0	38.80	38.80	27.0	92	663	460
30	4880	4620	0	40.89	40.89	23.5	111	775	537
65	3480	3300	0	53.16	53.16	23.2	15	789	547
100	2420	-	-	68.93	-	22.3	35	824	572

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.54. Carbon removal in C75 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	11820	0	-	42.15	33.3	-	-	-
3	10460	10300	0	43.56	43.56	30.6	265	265	159
6	9080	8780	0	46.76	46.76	27.8	193	457	276
10	8780	8600	0	44.83	44.83	26.2	110	567	342
13	7740	7600	0	43.83	43.83	26.2	121	689	415
20	7380	6880	0	44.85	44.85	25.7	22	711	428
30	6120	5880	0	46.97	46.97	23.9	106	817	492
65	4860	4600	80	52.87	51.95	23.4	58	875	527
100	3900	-	-	59.64	-	22.5	37	911	549

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.55. Carbon removal in C100 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	Water $_{added}$ (g)	TS[1] $_{out}$ (%)	TS$_{in}$ (%)	C[2] (%, dm^3)	C$_{removed}$[4] (g)	Accumulated C$_{removed}$[5] (g)	RCR[6] (g/kg C $_{added}$)
0	-	10440	0	-	41.10	24.5	-	-	-
3	9480	9250	0	41.70	41.70	23.8	110	110	105
6	8440	8840	600	45.31	42.24	23.2	31	141	134
10	8320	7900	0	43.85	43.85	22.2	56	197	188
13	7700	7140	0	45.01	45.01	22.2	1	199	189
20	6720	6260	0	43.56	43.56	22.3	59	258	245
30	5380	5100	0	45.83	45.83	21.9	68	326	310
65	4000	3800	120	56.60	54.82	21.6	23	349	332
100	2920	-	-	68.61	-	21.5	20	369	351

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ at day 3= Mass$_{in}$*TS$_{in}$*C (at day 0)- Mass $_{out}$*TS$_{out}$*C (at day 3).
[5] Accumulated C $_{removed}$ at day 6= Accumulated C $_{removed}$ at day 3+ C $_{removed}$ at day 6.
[6] Relative Carbon removal (g/kg C $_{added}$) = Accumulated C $_{removed}$ / C added at day 0.

Table C.56. Summary of accumulated carbon removal during composting (g).

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	0	0	0	0	0	0	0	0
3	96	95	215	333	440	265	265	110
6	204	240	404	499	534	349	457	141
10	261	282	461	590	629	466	567	197
13	277	364	549	699	799	571	689	199
20	394	415	611	775	874	663	711	258
30	449	446	663	863	1024	775	817	326
65	466	490	663	866	1036	789	875	349
100	466	490	672	882	1065	824	911	369

Table C.57. Summary of biodegradable carbon (C_{bio}) during composting (g)[1].

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	466	490	672	882	1065	824	919	369
3	370	395	458	549	625	560	646	258
6	263	250	268	383	531	476	454	227
10	206	208	211	293	436	359	344	171
13	189	126	123	183	265	254	222	170
20	73	75	62	108	190	161	200	111
30	18	45	9	19	41	50	94	43
65	0	0	9	16	29	35	36	20
100	0	0	0	0	0	0	0	0

[1]C_{bio} was calculated based on the assumption that all the biodegradable carbon was removed after 100 days of composting. Therefore the initial C_{bio} was equal to the accumulated $C_{removed}$ after 100 days.

Table C.58. Summary of biodegradable carbon (C_{bio}) during composting (%, dm)[1].

Day	C0	C10	C20	C30	C40	C50	C75	C100
0	18.23	19.83	22.30	23.76	23.11	19.24	18.52	8.59
3	13.89	11.59	15.35	15.98	16.40	14.63	14.41	6.69
6	10.45	12.07	10.54	14.50	14.98	11.59	11.06	5.68
10	11.19	11.03	12.39	12.73	13.16	11.21	8.92	4.94
13	11.25	8.04	8.48	9.46	9.82	9.64	6.69	5.28
20	5.30	6.34	5.37	6.67	8.13	7.50	6.50	4.06
30	1.43	4.38	0.93	1.47	2.09	2.63	3.43	1.82
65	0.00	0.00	0.85	1.24	1.63	2.00	1.42	0.92
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1]C_{bio} (%, dm) @ day 0= C_{bio} (g) @ day 0/ (wet mass (g) *TS (%) @ day0).

Table C.59. Ammonium nitrogen (NH_4-N) content changes during composting (mg.kg^{-1} DM).

	Day							
Reactor	0	6	10	13	20	30	65	100
C0-1	847	2427	1718	1854	655	447	227	78
C0-2	912	2041	1763	1900	611	500	227	79
C10-1	1904	2944	2436	2378	1256	603	419	280
C10-2	1997	2756	2621	2296	1371	658	425	294
C20-1	3296	2485	2072	2245	2033	436	167	132
C20-2	3531	2429	2296	2117	1949	504	177	129
C30-1	3553	2652	2296	2055	1137	1241	546	435
C30-2	3327	2719	2562	2014	1026	1266	528	425
C40-1	5096	5028	2087	3082	2186	2041	730	496
C40-2	5034	4923	2021	2903	2272	2364	734	492
C50-1	4859	3168	1625	2774	2225	2177	785	312
C50-2	5314	3114	1696	2871	2123	2085	782	309
C75-1	5334	3835	3701	3343	1918	1911	465	64
C75-2	5093	3741	3310	3800	2180	1749	452	62
C100-1	6133	2960	1583	1576	790	393	102	51
C100-2	6260	2540	1634	1660	809	423	95	50

Table C.60. Summary of ammonium nitrogen (NH_4-N) content changes during composting (mg.kg^{-1} DM).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	879±46	1,951±65	3,414±166	3,440±160	5,065±44	5,086±322	5,213±170	6,197±90
6	2,234±273	2,850±133	2,457±40	2,685±48	4,976±74	3,141±38	3,788±67	2,750±297
10	1,741±32	2,528±131	2,184±158	2,429±188	2,054±47	1,661±50	3,505±277	1,609±36
13	1,877±33	2,337±57	2,181±90	2,034±29	2,992±126	2,823±69	3,572±323	1,618±59
20	633±31	1,314±81	1,991±59	1,081±78	2,229±61	2,174±72	2,049±185	799±13
30	473±38	631±38	470±48	1,253±18	2,203±228	2,131±65	1,830±115	408±21
65	227±0	422±5	172±7	537±13	732±3	784±2	458±9	99±4
100	78±1	287±10	131±2	430±7	494±3	310±2	63±1	51±0

Table C.61. Nitrate nitrogen (NO_3-N) changes during composting (mg.kg^{-1} DM).

	Day							
Reactor	0	6	10	13	20	30	65	100
C0-1	5.3	6.6	3.2	2.6	7.1	2.7	27.7	121.7
C0-2	5.0	7.0	3.2	3.2	6.2	2.6	28.3	120.3
C10-1	2.6	4.7	5.4	3.6	9.0	3.1	4.4	102.4
C10-2	2.2	4.9	5.1	3.5	10.1	3.2	3.7	105.5
C20-1	1.7	5.1	2.4	2.6	4.7	5.1	3.4	141.3
C20-2	1.8	5.5	2.4	2.6	5.9	5.5	3.6	146.6
C30-1	2.2	5.4	2.7	3.2	3.2	3.2	2.8	215.6
C30-2	2.9	5.4	2.8	3.6	3.1	3.3	2.9	205.5
C40-1	3.5	2.3	2.4	5.7	5.1	3.2	2.3	234.5
C40-2	3.3	2.3	2.4	5.7	5.0	3.6	3.7	241.5
C50-1	4.1	4.0	3.3	3.3	5.0	2.8	3.9	368.1
C50-2	3.9	3.4	2.9	3.7	5.5	3.3	3.9	369.5
C75-1	2.9	2.1	2.3	4.4	6.6	2.3	44.8	447.8
C75-2	4.0	2.0	3.2	4.5	6.8	2.2	43.5	435.7
C100-1	4.2	2.8	3.6	2.5	2.5	3.4	4.7	291.8
C100-2	4.2	3.1	3.6	2.6	2.6	3.0	2.2	331.2

Table C.62. Summary of nitrate nitrogen (NO_3-N) content changes during composting (mg.kg^{-1} DM).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	5.1±0.2	2.4±0.3	1.7±0.1	2.5±0.5	3.4±0.1	4.0±0.2	3.4±0.8	4.2±0.0
6	6.8±0.3	4.8±0.1	5.3±0.3	5.4±0.0	2.3±0.0	3.7±0.5	2.1±0.1	3.0±0.2
10	3.2±0.0	5.2±0.2	2.4±0.0	2.7±0.1	2.4±0.0	3.1±0.3	2.7±0.7	3.6±0.0
13	2.9±0.4	3.6±0.1	2.6±0.0	3.4±0.3	5.7±0.0	3.5±0.3	4.5±0.0	2.6±0.1
20	6.6±0.6	9.5±0.8	5.3±0.9	3.2±0.1	5.1±0.1	5.2±0.3	6.7±0.2	2.5±0.0
30	2.7±0.1	3.1±0.1	5.3±0.3	3.2±0.1	3.4±0.3	3.0±0.3	2.3±0.1	3.2±0.3
65	28.0±0.4	4.0±0.5	3.5±0.2	2.8±0.0	3.0±1.0	3.9±0.0	44.2±0.9	3.5±1.8
100	121.0±0.9	103.9±2.2	144.0±3.8	210.5±7.2	238.0±4.9	368.8±1.0	441.8±8.5	311.5±27.9

Table C.63. pH changes during composting.

	Day								
Reactor	0	3	6	10	13	20	30	65	100
C0-1	6.13	7.62	8.11	8.53	8.53	8.70	8.29	8.04	7.56
C0-2	5.98	7.58	8.26	8.34	8.66	8.67	8.77	8.46	7.67
C10-1	6.75	8.02	8.30	8.62	8.93	9.07	8.89	8.13	7.97
C10-2	6.32	7.96	8.46	8.64	8.96	9.17	8.98	8.32	8.13
C20-1	7.21	8.12	8.45	8.84	8.84	9.22	8.77	8.07	8.29
C20-2	6.97	8.07	8.60	8.75	8.88	9.17	9.11	8.57	8.35
C30-1	7.80	8.33	8.62	8.80	8.95	9.12	8.90	8.81	8.26
C30-2	7.87	8.54	8.57	8.78	8.92	9.00	9.04	8.69	8.46
C40-1	7.95	8.28	8.63	8.75	8.89	9.13	8.98	8.90	7.93
C40-2	7.85	8.41	8.55	8.88	8.88	9.08	9.04	8.60	8.14
C50-1	8.38	8.36	8.78	8.92	9.07	9.22	9.00	8.76	7.78
C50-2	8.10	8.63	8.71	8.93	9.11	9.18	9.16	8.80	7.84
C75-1	8.37	8.69	8.88	8.95	9.08	9.14	9.08	8.87	7.74
C75-2	8.44	8.72	8.80	8.97	9.08	9.16	9.11	8.66	8.16
C100-1	8.51	8.68	8.87	9.10	9.21	9.23	9.11	8.84	8.00
C100-2	8.47	8.80	8.80	9.15	9.13	9.17	8.97	8.73	8.03

Table C.64. Summary of pH changes during composting.

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	6.06±0.11	6.54±0.30	7.09±0.17	7.84±0.05	7.90±0.07	8.24±0.20	8.41±0.05	8.49±0.03
3	7.60±0.03	7.99±0.04	8.10±0.04	8.44±0.15	8.35±0.09	8.50±0.19	8.71±0.02	8.74±0.08
6	8.19±0.11	8.38±0.11	8.53±0.11	8.60±0.04	8.59±0.06	8.75±0.05	8.84±0.06	8.84±0.05
10	8.44±0.13	8.63±0.01	8.80±0.06	8.79±0.01	8.82±0.09	8.93±0.01	8.96±0.01	9.13±0.04
13	8.60±0.09	8.95±0.02	8.86±0.03	8.94±0.02	8.89±0.01	9.09±0.03	9.08±0.00	9.17±0.06
20	8.69±0.02	9.12±0.07	9.20±0.04	9.06±0.08	9.11±0.04	9.20±0.03	9.15±0.01	9.20±0.04
30	8.53±0.34	8.94±0.06	8.94±0.24	8.97±0.10	9.01±0.04	9.08±0.11	9.10±0.02	9.04±0.10
65	8.25±0.30	8.23±0.13	8.32±0.35	8.75±0.08	8.75±0.21	8.78±0.03	8.77±0.15	8.79±0.08
100	7.62±0.08	8.05±0.11	8.32±0.04	8.36±0.14	8.04±0.15	7.81±0.04	7.95±0.30	8.02±0.02

Table C.65. Electrical conductivity changes during composting (μS.cm^{-1}).

	Day								
Reactor	0	3	6	10	13	20	30	65	100
C0-1	6.13	7.62	8.11	8.53	8.53	8.70	8.29	8.04	7.56
C0-2	5.98	7.58	8.26	8.34	8.66	8.67	8.77	8.46	7.67
C10-1	6.75	8.02	8.30	8.62	8.93	9.07	8.89	8.13	7.97
C10-2	6.32	7.96	8.46	8.64	8.96	9.17	8.98	8.32	8.13
C20-1	7.21	8.12	8.45	8.84	8.84	9.22	8.77	8.07	8.29
C20-2	6.97	8.07	8.60	8.75	8.88	9.17	9.11	8.57	8.35
C30-1	7.80	8.33	8.62	8.80	8.95	9.12	8.90	8.81	8.26
C30-2	7.87	8.54	8.57	8.78	8.92	9.00	9.04	8.69	8.46
C40-1	7.95	8.28	8.63	8.75	8.89	9.13	8.98	8.90	7.93
C40-2	7.85	8.41	8.55	8.88	8.88	9.08	9.04	8.60	8.14
C50-1	8.38	8.36	8.78	8.92	9.07	9.22	9.00	8.76	7.78
C50-2	8.10	8.63	8.71	8.93	9.11	9.18	9.16	8.80	7.84
C75-1	8.37	8.69	8.88	8.95	9.08	9.14	9.08	8.87	7.74
C75-2	8.44	8.72	8.80	8.97	9.08	9.16	9.11	8.66	8.16
C100-1	8.51	8.68	8.87	9.10	9.21	9.23	9.11	8.84	8.00
C100-2	8.47	8.80	8.80	9.15	9.13	9.17	8.97	8.73	8.03

Table C.66. Summary of electrical conductivity changes during composting (μS.cm^{-1}).

Day	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
0	875±23	895±40	1,044±127	1,130±148	1,153±36	1,242±54	1,367±135	1,075±98
3	822±13	851±58	917±14	764±55	1,198±148	1,065±23	747±62	403±21
6	897±33	543±58	880±36	969±50	815±264	840±37	558±191	274±8
10	1,003±196	635±47	867±208	909±166	756±22	923±5	739±179	571±166
13	883±44	689±12	893±40	929±72	947±62	804±41	663±28	560±3
20	538±56	523±42	555±91	745±43	681±58	597±136	566±67	419±2
30	643±41	658±57	701±8	696±59	668±33	709±24	613±13	404±22
65	1,240±76	1,202±93	1,285±13	1,262±96	1,291±95	1,056±52	863±86	729±91
100	1,463±163	1,572±124	1,587±105	1,581±72	1,516±122	1,490±70	843±71	992±15

APPENDIX D: Chapter 4 Supplementary Data

Table D.1. Bacterial and fungal diversity in the reactors.

Reactor	Sampling day	Richness Bacteria/Fungi	Evenness Bacteria/Fungi	Simpson index Bacteria/Fungi
C0	0	75/26	0.43/0.34	0.71/0.59
	6	72/24	0.55/0.30	0.83/0.45
	30	130/8	0.69/0.32	0.94/0.45
	100	82/17	0.81/0.35	0.95/0.56
C10	6	72/25	0.55/0.47	0.810.69
	30	115/8	0.62/0.11	0.89/0.08
	100	158/10	0.65/0.42	0.91/0.55
C20	6	77/35	0.6/0.34	0.88/0.60
	30	139/12	0.68/0.24	0.93/0.35
	100	167/14	0.71/0.41	0.97/0.58
C30	6	116/29	0.620.51	0.91/0.74
	30	136/9	0.75/0.31	0.96/0.40
	100	150/13	0.71/0.46	0.95/0.60
C40	6	79/38	0.62/0.36	0.89/0.63
	30	134/25	0.69/0.26	0.94/0.38
	100	150/11	0.76/0.35	0.96/0.45
C50	6	98/34	0.69/0.55	0.93/0.80
	30	121/35	0.62/0.35	0.87/0.61
	100	177/14	0.74/0.10	0.96/0.09
C75	6	107/58	0.64/0.47	0.90/0.75
	30	122/21	0.68/0.13	0.92/0.13
	100	154/13	0.72/0.06	0.95/0.06
C100	0	48/8	0.48/0.44	0.67/0.39
	6	84/31	0.54/0.30	0.83/0.43
	30	93/9	0.46/0.08	0.73/0.06
	100	161/15	0.66/0.19	0.93/0.24

Table D.2. Abundance of phylum level of bacteria community in the feedstock at the initial stage (day 0) of composting (%).

Phylum	**C0 (OFMSW)**	**C100 (digestate)**
Actinobacteria	2.8	0.0
Bacteroidetes	0.4	10.3
Firmicutes	63.5	31.2
Proteobacteria	32.6	0.1
Thermotogae	0.1	55.0
Unassigned and Others	0.3	3.6

Table D.3. Abundance of phylum level of bacteria community in the reactors at day 6 of composting (%).

Phylum	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria	7.3	0.6	6.2	6.6	3.2	4.3	2.1	1.0
Bacteroidetes	0.1	0.2	0.1	1.3	0.2	1.4	3.9	0.8
Firmicutes	69.8	76.2	57.2	68.0	58.7	59.7	63.5	37.9
Gemmatimonadetes	0.3	0.2	0.5	1.1	0.1	0.5	0.1	0.2
Proteobacteria	19.7	10.6	32.1	7.7	23.8	14.0	4.6	37.8
Synergistetes	0.0	0.0	0.1	0.6	0.4	1.1	3.4	0.6
Thermotogae	0.0	0.0	0.1	4.7	1.9	9.3	13.0	17.8
Deinococcus-Thermus	0.2	0.1	0.1	1.8	6.2	1.5	0.0	0.0
Unassigned and others	2.1	12.1	3.2	7.8	5.2	7.9	9.1	3.9

Table D.4. Abundance of phylum level of bacteria community in the reactors at day 30 of composting (%).

Phylum	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria	7.7	1.7	13.8	15.0	7.0	1.7	3.7	0.8
Bacteroidetes	8.1	27.2	14.3	17.4	25.0	10.8	15.7	56.4
Chloroflexi	5.9	14.9	8.7	5.1	5.7	5.0	10.6	16.0
Firmicutes	1.4	19.2	2.9	4.6	13.8	45.2	24.9	2.3
Gemmatimonadetes	9.5	1.0	3.2	6.3	5.8	2.6	2.2	2.7
Proteobacteria	59.9	31.4	51.9	43.7	33.0	27.7	37.7	19.0
C. Saccharibacteria	2.4	0.3	0.4	0.5	0.3	0.5	0.6	0.5
Deinococcus-Thermus	0.8	0.4	0.7	2.5	3.0	1.2	0.3	1.4
Unassigned and others	3.9	4.0	4.0	4.4	6.1	5.2	4.2	1.3

Table D.5. Abundance of phylum level of bacteria community in the reactors at day 100 of composting (%).

Phylum	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria	16.4	7.5	25.3	37.5	22.3	18.6	17.3	13.4
BRC1	1.1	0.1	0.9	0.4	0.1	0.1	0.1	0.1
Bacteroidetes	7.5	2.6	7.4	4.7	6.9	7.8	13.7	16.0
Chloroflexi	12.9	49.0	15.9	10.9	19.3	21.2	8.1	38.5
Firmicutes	10.1	6.9	10.9	8.1	8.1	7.8	5.2	4.7
Gemmatimonadetes	3.2	0.9	3.1	2.4	2.5	2.1	1.3	1.1
Proteobacteria	41.0	26.5	30.4	29.4	31.1	33.6	39.6	20.2
C. Saccharibacteria	1.0	0.5	0.4	0.2	0.4	0.8	0.5	1.0
Tenericutes	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
Deinococcus-Thermus	0.6	0.4	1.0	0.7	1.1	1.8	0.5	1.3
Unassigned and others	6.2	5.8	5.1	5.5	7.7	6.2	12.5	4.1

Table D.6. Abundance of bacterial taxonomy in the feedstock at the initial stage (day 0) of composting (%).

Taxonomy	**C0**	**C100**
Bacteroidetes;__Bacteroidia;__Bacteroidales	0.0	2.3
Bacteroidetes__Bacteroidia__Bacteroidales__Porphyromonadaceae	0.0	7.7
Firmicutes__Bacilli__Bacillales__Bacillaceae__Bacillus	3.9	0.0
Firmicutes__Bacilli__Bacillales__Planococcaceae	6.9	0.1
Firmicutes__Bacilli__Bacillales__Planococcaceae__Lysinibacillus	1.8	0.0
Firmicutes__Bacilli__Lactobacillales	1.3	0.0
Firmicutes__Bacilli__Lactobacillales__Lactobacillaceae	30.9	0.0
Firmicutes__Bacilli__Lactobacillales__Lactobacillaceae__Lactobacillus	14.5	0.0
Firmicutes__Clostridia	0.0	1.1
Firmicutes__Clostridia__Clostridiales__Caldicoprobacteraceae__Caldicoprobacter	0.0	8.6
Firmicutes__Clostridia__Clostridiales__Clostridiaceae__Clostridium	0.0	1.0
Firmicutes__Clostridia__Halanaerobiales__Halanaerobiaceae	0.0	1.1
Firmicutes__Clostridia__MBA08	0.0	6.4
Firmicutes__Clostridia__OPB54	0.0	5.0
Firmicutes__Clostridia__SHA-98	0.0	2.1
Firmicutes__OPB54	0.0	1.2
Proteobacteria__Alphaproteobacteria__Rhizobiales__Rhizobiaceae__Agrobacterium	1.0	0.0
Proteobacteria__Alphaproteobacteria__Sphingomonadales__Sphingomonadaceae__Sphingomonas	1.2	0.0
*Proteobacteria__Gammaproteobacteria__Enterobacteriales__Enterobacteriaceae_*	9.4	0.0
Proteobacteria__Gammaproteobacteria__Enterobacteriales__Enterobacteriaceae__Proteus	15.2	0.0
Thermotogae__Thermotogae__Thermotogales__Thermotogaceae__S1	0.1	55.0
Other[1]	13.5	5.8
Unassigned	0.3	2.6

[1] Sequences with less than 1% abundance.

Table D.7. Abundance of bacterial taxonomy in the reactors at day 6 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria__Actinobacteria__Actinomycetales	2.5	0.1	2.2	3.4	1.1	0.8	0.1	0.0
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiopsaceae	1.5	0.1	1.7	2.0	0.9	2.0	0.6	0.4
Bacteroidetes__Bacteroidia__Bacteroidales__Porphyromonadaceae	0.0	0.1	0.0	1.1	0.1	1.2	3.4	0.7
Firmicutes__Bacilli__Bacillales	1.9	2.9	2.1	17.2	14.6	16.6	22.5	17.8
Firmicutes__Bacilli__Bacillales__Bacillaceae__Bacillus	15.3	3.1	8.1	5.1	2.8	4.3	0.8	0.2
Firmicutes__Bacilli__Bacillales__Bacillaceae__Geobacillus	2.5	0.3	1.0	0.5	0.2	0.1	0.0	0.0
Firmicutes__Bacilli__Bacillales__Planococcaceae	0.5	1.3	0.2	0.0	0.0	0.1	0.1	0.0
Firmicutes__Bacilli__Bacillales__Planococcaceae	31.0	35.9	21.3	10.4	5.3	2.5	0.4	0.1
Firmicutes__Bacilli__Bacillales__Planococcaceae__Lysinibacillus	1.5	0.4	1.0	0.1	0.1	0.0	0.0	0.0
Firmicutes__Bacilli__Bacillales__Planococcaceae__Sporosarcina	0.1	0.0	0.1	0.0	0.1	1.1	0.5	0.2
Firmicutes__Bacilli__Bacillales__Planococcaceae__Ureibacillus	0.2	1.7	0.1	0.1	0.2	0.4	0.6	0.1
Firmicutes__Bacilli__Bacillales__Thermoactinomycetaceae__Planifilum	12.9	0.1	18.3	13.3	19.8	4.7	1.1	0.0
Firmicutes__Bacilli__Haloplasmatales__Haloplasmataceae	0.0	1.0	0.0	0.2	0.0	0.1	0.1	0.1
Firmicutes__Clostridia	0.0	0.2	0.0	0.3	0.0	1.2	2.7	1.7
Firmicutes__Clostridia	1.5	2.4	2.1	11.0	4.6	4.2	2.6	0.9
Firmicutes__Clostridia__Clostridiales__Caldicoprobacteraceae__Caldicoprobacter	0.1	0.4	0.3	1.4	5.1	6.0	10.0	3.4
Firmicutes__Clostridia__Clostridiales__Clostridiaceae__Clostridium	0.0	2.4	0.0	0.3	0.3	1.1	0.4	0.5
Firmicutes__Clostridia__Clostridiales__Symbiobacteriaceae__Symbiobacterium	0.4	4.9	0.4	2.2	1.9	2.6	0.3	0.9

Table D.7. (continued)

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Firmicutes__Clostridia__Clostridiales__[Tissierellaceae]	0.0	10.4	0.1	0.7	0.8	0.8	1.8	0.2
Firmicutes__Clostridia__Clostridiales__Tissierellaceae__Tepidimicrobium	0.0	0.6	0.1	0.7	0.5	1.3	2.8	2.2
Firmicutes__Clostridia__Halanaerobiales__Halanaerobiaceae	0.0	0.0	0.0	0.0	0.0	0.2	0.6	0.4
Firmicutes__Clostridia__MBA08	0.0	2.9	0.0	0.8	0.2	6.9	4.3	3.9
Firmicutes__Clostridia__Natranaerobiales__Anaerobrancaceae__A55_D21	0.0	0.0	0.0	0.2	0.1	0.2	1.2	0.1
Firmicutes__Clostridia__OPB54	0.0	0.7	0.0	0.6	0.1	0.9	3.5	2.0
Firmicutes__Clostridia__SHA-98	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Firmicutes__Clostridia__SHA-98	0.0	0.0	0.0	0.1	0.1	0.4	1.0	0.3
Gemmatimonadetes__Gemm-5	0.3	0.2	0.5	1.1	0.1	0.5	0.1	0.1
Proteobacteria__Alphaproteobacteria__Rhizobiales	7.4	2.0	12.6	2.5	2.7	3.4	0.4	0.5
Proteobacteria__Alphaproteobacteria__Rhizobiales__Beijerinckiaceae	5.8	0.4	8.7	0.9	1.1	1.7	0.1	0.1
Proteobacteria__Alphaproteobacteria__Rhizobiales__Brucellaceae__Ochrobactrum	0.8	0.1	1.3	0.3	0.1	0.1	0.1	0.0
Proteobacteria__Alphaproteobacteria__Rhizobiales__Hyphomicrobiaceae	0.7	0.5	1.7	0.6	0.3	0.5	0.0	0.1
Proteobacteria__Gammaproteobacteria	0.0	0.1	0.0	0.3	0.9	4.5	1.2	3.5
Proteobacteria__Gammaproteobacteria__Pseudomonadales__Pseudomonadaceae	0.5	2.2	1.2	0.4	16.4	0.4	0.7	29.5
Proteobacteria__Gammaproteobacteria__Pseudomonadales__Pseudomonadaceae__Pseudomonas	0.0	0.8	0.0	0.0	0.0	0.0	0.5	1.6
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae	1.8	2.0	2.9	1.3	1.4	2.5	0.4	1.0

Table D.7. (continued)

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Synergistetes__Synergistia__Synergistales__Dethiosulfovibrionaceae__Aminobacterium	0.0	0.0	0.0	0.2	0.0	0.7	2.4	0.0
Thermotogae__Thermotogae__Thermotogales__Thermotogaceae	0.0	0.0	0.1	4.7	1.9	9.3	13.0	17.8
Thermi__Deinococci__Thermales__Thermaceae__Thermus	0.1	0.0	0.0	1.6	6.2	1.5	0.0	0.0
Other[1]	8.6	7.7	8.7	6.6	4.8	7.3	10.5	5.8
Unassigned	2.1	12.1	3.2	7.8	5.2	7.9	9.1	3.9

[1] Sequences with the abundancy of less than 1%.

Table D.8. Abundance of bacterial taxonomy in the reactors at day 30 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria__Actinobacteria__Actinomycetales	0.3	0	0.7	1.1	0.4	0	0	0
Actinobacteria__Actinobacteria__Actinomycetales	3.2	0	5.2	4.8	0.5	0	0.2	0
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiopsaceae	0.5	0.1	1	1.9	1.8	0.1	0.7	0.2
Actinobacteria__Actinobacteria__Actinomycetales__Streptosporangiaceae__ Nonomuraea	1	0.1	2.8	1.8	0.2	0.1	0.2	0.2
Actinobacteria__Actinobacteria__Actinomycetales__Thermomonosporaceae_ _Actinomadura	1.5	0.2	1.7	2.6	2.1	0.2	1	0.2
Bacteroidetes__Bacteroidia__Bacteroidales__Marinilabiaceae	0	0.7	0	0	1.7	0.1	0.6	0
Bacteroidetes__Bacteroidia__Bacteroidales__Marinilabiaceae	0.8	22.5	0.2	0.3	8.9	8.5	10.2	0.6
Bacteroidetes__Cytophagia__Cytophagales__Cytophagaceae	3.6	1.6	5.7	7.3	12.9	0.8	2.7	48.2
Bacteroidetes__Saprospirae__Saprospirales__Chitinophagaceae	1.3	1.2	5.3	4.9	0.8	0.7	1.7	7.1
Bacteroidetes__Saprospirae__Saprospirales__Chitinophagaceae__Niabella	0.9	0	2	3.2	0	0	0	0
Chloroflexi__Anaerolineae__CFB-26	0	5.3	0.2	0.6	1.5	2.4	6.4	6.3
Chloroflexi__Anaerolineae__SBR1031__A4b	1.5	1.5	2.3	2.2	2	1	1.4	0.9
Chloroflexi__Anaerolineae__SBR1031__SHA-31	0.1	6	0.2	0.1	0.2	0.4	0.4	7.6
Chloroflexi__Chloroflexi__Chloroflexales	2.4	0.6	3.8	0.6	0.5	0.4	1.2	0.2
Chloroflexi__Chloroflexi__Roseiflexales	0.9	1.1	1.3	0.3	0.5	0.2	0.8	0.5
Firmicutes__Clostridia	0	0.4	0	0.2	0.6	2.7	2.1	0
Firmicutes__Clostridia	0.3	0.2	0.1	0.7	2.9	2.1	1.2	0.1

Table D.8. (continued)

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Firmicutes__Clostridia__Clostridiales__Clostridiaceae__Clostridium	0.1	0.3	0	0.1	0.2	2	0.5	0
*Firmicutes__Clostridia__MBA08_*	0.1	15.8	0.4	1	6	31.6	13.7	1.6
Firmicutes__Clostridia__OPB54	0	0.6	0.3	0.5	0.8	1.5	1.9	0.1
Gemmatimonadetes__Gemm-3	7.2	0.3	1.4	2.5	0.8	0.5	0.4	0.2
Gemmatimonadetes__Gemm-5	2	0.7	1.6	3.6	5	2.1	1.8	2.4
Proteobacteria__Alphaproteobacteria__Rhizobiales	1.1	1.5	1.8	2.1	0.8	0.5	0.8	0.3
Proteobacteria__Alphaproteobacteria__Rhizobiales__Beijerinckiaceae	0.5	0	0.6	1.3	0.3	0.1	0.1	0.1
Proteobacteria__Alphaproteobacteria__Rhizobiales__Hyphomicrobiaceae	5	1.4	5.9	8.1	2.5	0.9	1.4	0.5
*Proteobacteria__Alphaproteobacteria__Rhizobiales__Hyphomicrobiaceae_*	0.7	0.2	0.8	1.1	0.3	0.1	0.2	0.2
Proteobacteria__Alphaproteobacteria__Rhizobiales__Phyllobacteriaceae	3.1	0.5	2.3	2.2	0.3	0.2	0.1	0.1
Proteobacteria__Alphaproteobacteria__Rhodospirillales__Rhodospirillaceae	1.4	0.3	0.8	1.3	0.9	0.5	0.4	0.4
Proteobacteria__Alphaproteobacteria__Sphingomonadales__Sphingomonadaceae	11.7	0.4	1.1	2.8	0.3	0.4	0.3	0
Proteobacteria__Betaproteobacteria	1.7	0.3	0.5	1	1	0.2	0.1	0.1
Proteobacteria__Betaproteobacteria__Burkholderiales__Alcaligenaceae	0.6	2.7	0.6	0.8	0.4	1.3	1	0.1
Proteobacteria__Deltaproteobacteria__Myxococcales	0.4	0.2	0.6	1.3	1.2	0.3	0.7	0.3
Proteobacteria__Gammaproteobacteria	1.5	1.1	1	1.6	1	2.7	2.3	0.8
Proteobacteria__Gammaproteobacteria	1.6	0.4	0.9	2.5	4.9	3.7	4.4	0.5

Table D.8. (continued)

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Proteobacteria__Gammaproteobacteria__Pseudomonadales__Pseudomonadaceae	5.1	11.8	21.1	3.5	11.5	11.1	18.3	12.5
Proteobacteria__Gammaproteobacteria__Thiotrichales__Piscirickettsiaceae	1.4	0.4	1.4	1	0.7	0.5	0.6	0.6
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Sinobacteracea	2.5	0.2	0.7	0.7	1.6	0.5	0.3	0.1
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Sinobacteracea_Steroidobacter	11.5	1.5	1.9	2.8	1.3	2.1	2.2	0.5
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae	3.4	2.4	4.7	4.9	0.7	0.3	0.5	0.4
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae__Luteimonas	0.3	1.1	0.1	0.1	0.6	0.6	2	0.3
*TM7__TM7-1_*	2	0.3	0.3	0.3	0.3	0.4	0.4	0.5
Thermi__Deinococci__Deinococcales__Trueperaceae__B-42	0.8	0.4	0.7	2.2	1.4	0.3	0.3	0.4
Thermi__Deinococci__Thermales__Thermaceae__Thermus	0	0	0	0.4	1.6	0.9	0	0
Other[1]	12.1	9.7	13	13.3	10	9.8	10.3	3.6
Unassigned	3.9	4	3	4.4	6.1	5.2	4.2	1.3

[1] Sequences with the abundancy of less than 1%.

Table D.9. Abundance of bacterial taxonomy in the reactors at day 100 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Actinobacteria__Acidimicrobiia__Acidimicrobiales	1.4	0.8	2.1	2.0	2.7	2.3	1.2	1.3
Actinobacteria__Actinobacteria__Actinomycetales	0.4	0.1	0.7	1.4	0.7	0.2	0.3	0.2
Actinobacteria__Actinobacteria__Actinomycetales	4.2	0.2	5.6	3.4	0.9	0.3	0.4	0.6
Actinobacteria__Actinobacteria__Actinomycetales__Intrasporangiaceae	0.5	0.8	1.3	0.8	0.7	0.4	0.4	0.7
Actinobacteria__Actinobacteria__Actinomycetales__Microbacteriaceae__Microbacterium	0.0	0.0	0.0	0.0	0.3	1.6	0.3	0.1
Actinobacteria__Actinobacteria__Actinomycetales__Mycobacteriaceae__Mycobacterium	0.9	0.6	1.5	0.8	0.9	0.6	1.0	0.3
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiaceae__Nocardia	0.0	0.3	0.1	0.2	0.3	0.4	1.0	0.4
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiaceae__Rhodococcus	0.2	0.9	0.3	0.2	0.8	4.1	0.6	0.2
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiopsaceae	2.8	0.6	3.9	14.0	5.5	2.4	3.5	2.2
Actinobacteria__Actinobacteria__Actinomycetales__Nocardiopsaceae	0.3	0.3	1.0	1.5	0.7	0.2	0.3	0.4
Actinobacteria__Actinobacteria__Actinomycetales__Pseudonocardiaceae	0.3	0.1	0.9	1.8	0.3	0.1	0.3	0.3
Actinobacteria__Actinobacteria__Actinomycetales__Streptomycetaceae__Streptomyces	0.7	0.5	1.0	1.4	1.0	0.7	1.3	1.4
Actinobacteria__Actinobacteria__Actinomycetales__Streptosporangiaceae__Nonomuraea	1.3	0.4	2.6	2.4	1.6	0.3	0.7	1.6
Actinobacteria__Actinobacteria__Actinomycetales__Thermomonosporaceae__Actinomadura	1.7	0.5	1.9	4.3	2.0	1.2	2.0	1.6
BRC1__PRR-11	1.1	0.1	0.9	0.4	0.1	0.1	0.1	0.1
Bacteroidetes__Bacteroidia__Bacteroidales__Prevotellaceae__Prevotella	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bacteroidetes__Cytophagia__Cytophagales__Cytophagaceae	1.7	0.9	2.4	1.9	4.1	2.9	2.5	12.0

Table D.9. (continued)

Taxonomy	C0	C10	C20	C30	C40	C50	C75	C100
Bacteroidetes__Sphingobacteriia__Sphingobacteriales__Sphingobacteriaceae	0.0	0.0	0.0	0.0	0.1	0.9	1.6	0.1
Bacteroidetes__Sphingobacteriia__Sphingobacteriales__Sphingobacteriaceae__Sphingobacterium	0.0	0.0	0.0	0.0	0.1	0.5	3.6	0.2
Bacteroidetes__Rhodothermi__Rhodothermales__Rhodothermaceae	1.1	0.3	1.9	1.4	0.5	0.3	0.2	0.4
Bacteroidetes__Saprospirae__Saprospirales__Chitinophagaceae	1.0	1.1	2.4	0.9	1.8	2.2	3.8	3.1
Chloroflexi__Anaerolineae__Ardenscatenales__Ardenscatenaceae__Ardenscatena	1.0	0.8	0.8	0.9	1.0	0.7	0.2	0.4
Chloroflexi__Anaerolineae__CFB-26	0.1	23.9	0.6	1.6	2.5	10.1	3.7	17.5
Chloroflexi__Anaerolineae__Caldilineales__Caldilineaceae	0.9	1.3	1.3	0.3	0.7	0.8	0.4	0.6
Chloroflexi__Anaerolineae__SBR1031__A4b	7.6	9.9	7.6	4.7	8.2	5.0	1.5	3.9
Chloroflexi__Anaerolineae __SBR1031__SHA-31	0.2	9.0	0.2	0.1	1.0	1.4	0.4	12.4
Chloroflexi__Chloroflexi__Chloroflexales	1.4	1.2	2.2	0.6	1.1	0.7	0.3	0.6
Chloroflexi__Chloroflexi__Roseiflexales	0.5	1.6	1.2	0.2	1.4	0.7	0.3	1.4
Chloroflexi__Thermomicrobia__Sphaerobacterales	1.0	0.7	0.9	1.5	2.8	1.3	0.7	0.5
Firmicutes__Bacilli__Bacillales	0.1	0.4	0.6	1.0	0.8	0.8	0.6	0.3
Firmicutes__Bacilli__Bacillales__Bacillaceae__Bacillus	3.3	1.2	3.2	2.8	2.5	2.2	0.8	0.4
Firmicutes__Bacilli__Bacillales__Bacillaceae__Geobacillus	2.2	0.6	1.2	0.4	0.1	0.1	0.0	0.0
Firmicutes__Bacilli__Bacillales__Thermoactinomycetaceae	0.2	1.5	0.6	0.7	0.8	1.1	1.5	2.1
Gemmatimonadetes__Gemm-3	1.9	0.5	1.5	1.0	0.7	0.6	0.3	0.2

Table D.9. (continued)

Taxonomy	C0	C10	C20	C30	C40	C50	C75	C100
Gemmatimonadetes__Gemm-5	1.3	0.4	1.4	1.4	1.8	1.5	0.8	0.8
Proteobacteria__Alphaproteobacteria	0.3	0.2	0.2	0.5	1.1	1.1	0.5	0.2
Proteobacteria__Alphaproteobacteria__Rhizobiales	1.5	3.5	2.5	2.0	2.5	1.9	2.0	2.0
Proteobacteria__Alphaproteobacteria__Rhizobiales__Hyphomicrobiaceae	4.3	4.4	8.8	9.8	5.3	3.6	3.5	2.1
Proteobacteria__Alphaproteobacteria__Rhizobiales__Phyllobacteriaceae	2.6	1.4	3.5	3.0	1.2	0.7	0.6	0.6
Proteobacteria__Alphaproteobacteria__Rhizobiales__Phyllobacteriaceae	1.0	1.1	0.3	0.6	0.6	0.7	0.5	0.3
Proteobacteria__Alphaproteobacteria__Rhizobiales__Phyllobacteriaceae__Defluvibacter	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.2
Proteobacteria__Alphaproteobacteria__Rhodospirillales__Rhodospirillaceae	1.0	0.6	0.9	0.7	0.9	0.7	0.8	0.6
Proteobacteria__Alphaproteobacteria__Sphingomonadales__Sphingomonadacea	1.1	0.2	0.8	0.5	0.1	0.2	0.1	0.1
Proteobacteria__Deltaproteobacteria__Myxococcales	0.6	0.6	1.3	0.9	1.1	1.0	0.6	0.6
Proteobacteria__Gammaproteobacteria	0.1	1.0	0.8	1.1	2.6	2.7	2.5	0.7
Proteobacteria__Gammaproteobacteria	0.6	0.5	0.7	0.9	1.2	0.8	0.5	0.4
Proteobacteria__Gammaproteobacteria__Pseudomonadales__Pseudomonadaceae	1.0	4.3	1.1	1.7	6.2	5.1	4.3	6.1
Proteobacteria__Gammaproteobacteria__Pseudomonadales__Pseudomonadacea__Pseudomonas	14.7	0.1	0.1	0.1	0.0	0.2	0.0	0.0
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Sinobacteraceae	1.8	0.3	0.8	0.4	1.7	1.1	0.2	0.1
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Sinobacteraceae_Steroidobacter	3.4	1.3	1.9	1.5	1.0	5.0	1.6	0.5
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae	0.6	0.3	1.3	0.6	0.3	1.6	10.9	0.4

Table D.9. (continued)

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae__Luteimonas	0.2	0.5	0.1	0.0	0.5	0.7	1.0	0.4
Proteobacteria__Gammaproteobacteria__Xanthomonadales__Xanthomonadaceae__Lysobacter	0.1	0.0	0.1	0.0	0.0	0.2	1.0	0.1
TM7__TM7-1	1.0	0.4	0.3	0.2	0.3	0.7	0.5	0.9
Tenericutes__Mollicutes__Anaeroplasmatales__Anaeroplasmataceae	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0
Thermi__Deinococci__Deinococcales__Trueperaceae__B-42	0.6	0.4	1.0	0.7	1.1	0.8	0.5	1.3
Other[1]	14.1	12.6	15.6	13.3	14.1	16.3	17.1	11.0
Unassigned	5.2	4.8	4.1	5.5	7.7	6.2	12.5	3.1

[1] Sequences with the abundancy of less than 1%.

Table D.10. Abundance of fungal taxonomy in the feedstock at the initial stage (day 0) of composting (%).

Taxonomy	**C0 (OFMSW)**	**C100 (digestate)**
Ascomycota_Eurotiomycetes _Eurotiales _Elaphomycetaceae _Xeromyces	0.0	3.3
Ascomycota _ Saccharomycetes _ Saccharomycetales _ Debaryomycetaceae _ Debaryomyces	0.0	2.7
Ascomycota _ Saccharomycetes _ Saccharomycetales _ Dipodascaceae _ Dipodascus	11.9	0.6
Ascomycota _ Saccharomycetes _ Saccharomycetales _Dipodascaceae _Galactomyces	40.2	77.0
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetaceae _Pichia	36.7	5.5
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetales _Candida	6.9	5.7
Basidiomycota _Tremellomycetes _Cystofilobasidiales _Cystofilobasidiales _Mrakiella	0.1	2.0
Basidiomycota _Tremellomycetes _Tremellales _Tremellales _ Trichosporon (Trichosporonales)	2.1	0.0
No Hit	0.3	3.2
Other[1]	1.7	0.0

[1] Sequences with the abundancy of less than 1%.

Table D.11. Abundance of fungal taxonomy in the reactors at day 6 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Ascomycota _Ascomycota_Ascomycota_Ascomycota_Thermomyces	72.5	0.7	2.4	2.8	0.3	0.0	0.7	12.2
Ascomycota _Eurotiomycetes _Eurotiales _Trichocomaceae _Aspergillus	0.0	1.5	0.0	2.0	0.0	8.6	0.7	0.8
Ascomycota _Eurotiomycetes _Eurotiales _Trichocomaceae _Emericella	0.0	0.0	0.0	0.0	0.0	0.2	0.5	2.5
Ascomycota _Eurotiomycetes _Eurotiales _Trichocomaceae _Penicillium	0.0	0.0	0.0	0.2	0.0	0.4	1.0	1.7
Ascomycota _Leotiomycetes _Helotiales _Helotiales_Scytalidium	0.0	0.4	0.0	0.0	0.0	0.0	0.0	74.1
Ascomycota _Saccharomycetes _Saccharomycetales _Debaryomycetaceae _Debaryomyces	0.0	0.0	0.1	0.1	0.0	3.1	3.5	0.1
Ascomycota _Saccharomycetes _Saccharomycetales _Debaryomycetaceae _Meyerozyma	0.0	0.2	0.0	1.0	0.2	1.9	1.5	0.0
Ascomycota _Saccharomycetes _Saccharomycetales _Dipodascaceae _Dipodascus	1.3	13.5	18.1	9.9	16.7	9.4	8.3	0.5
Ascomycota _Saccharomycetes _Saccharomycetales _Dipodascaceae _Galactomyces	4.5	32.1	39.1	28.1	36.8	19.2	33.1	1.1
Ascomycota _Saccharomycetes _Saccharomycetales _Metschnikowiaceae _Clavispora	0.5	0.9	0.5	1.0	0.7	1.9	0.8	0.0
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetaceae _Pichia	11.8	17.0	21.7	20.0	16.5	28.9	20.0	0.6
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetales _Candida	8.3	25.7	15.8	27.0	23.8	14.2	17.6	0.5
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetales_Ogataea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ascomycota _Saccharomycetes _Saccharomycetales _Wickerhamomycetaceae _Wickerhamomyces	0.3	0.6	0.8	1.2	1.7	4.5	2.4	0.1
Ascomycota _Sordariomycetes _Hypocreales _Hypocreales; Cephalosporium	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.7
Ascomycota _Sordariomycetes _Hypocreales _Hypocreales_Eucasphaeria	0.0	0.0	0.0	0.0	0.0	0.0	0.4	1.9
Basidiomycota _Tremellomycetes _Cystofilobasidiales _Cystofilobasidiales_Mrakiella	0.1	0.2	0.1	0.5	0.2	2.0	1.1	0.2
Mortierellales _Mortierellaceae _Mortierella	0.0	0.1	0.0	0.0	0.5	0.1	1.8	0.2

Table D.11. continued

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
No Hit	0.0	4.7	0.3	0.8	0.4	1.1	0.9	0.4
Other[1]	0.5	2.5	1.0	5.5	2.1	4.4	5.1	1.3

[1] Sequences with the abundancy of less than 1%.

Table D.12. Abundance of fungal taxonomy in the reactors at day 30 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Ascomycota _Ascomycota_Ascomycota_Ascomycota_Thermomyces	33.1	2.1	21.3	73.6	3.5	4.8	1.2	1.0
Ascomycota _Eurotiomycetes _Eurotiales _Trichocomaceae _Talaromyces	0.0	0.0	0.3	1.7	4.8	0.1	0.9	0.0
Ascomycota _Leotiomycetes _Helotiales _Helotiales_Scytalidium	66.4	95.7	77.5	23.9	77.7	42.0	93.0	97.2
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetaceae _Pichia	0.0	0.1	0.1	0.1	1.3	2.6	0.8	0.1
Ascomycota _Saccharomycetes _Saccharomycetales _Saccharomycetales_Candida	0.0	0.2	0.1	0.1	0.4	1.6	0.2	0.0
Ascomycota _Sordariomycetes _Sordariales _Chaetomiaceae _Chaetomium	0.0	0.0	0.0	0.0	0.0	0.1	1.0	0.0
No Hit	0.4	1.8	0.6	0.5	11.4	45.3	2.4	0.6
Other[1]	0.1	0.1	0.1	0.2	0.9	3.5	0.6	1.1

[1] Sequences with the abundancy of less than 1%.

Table D.13. Abundance of fungal taxonomy in the reactors at day 100 of composting (%).

Taxonomy	**C0**	**C10**	**C20**	**C30**	**C40**	**C50**	**C75**	**C100**
Ascomycota _Eurotiomycetes _Eurotiales _Aspergillaceae _Aspergillus	0.2	0.4	1.1	1.5	0.7	0.6	0.0	0.5
Ascomycota _Eurotiomycetes _Eurotiales _Trichocomaceae _Thermomyces	36.2	1.3	27.0	56.6	0.5	0.0	0.0	0.1
Ascomycota _Leotiomycetes _Unclassified _Unclassified _Scytalidium	55.5	54.4	57.4	11.3	6.3	2.3	0.0	0.0
Ascomycota _Orbiliomycetes _Orbiliales _Orbiliaceae _Arthrobotrys	0.0	0.0	0.0	0.0	0.1	0.4	0.4	8.9
Ascomycota _Sordariomycetes _Hypocreales _Unclassified _Trichothecium	0.2	0.0	0.0	0.0	0.1	0.0	0.1	1.1
Ascomycota _Sordariomycetes _Microascales _Microascaceae _Petriella	0.0	0.0	0.0	0.2	0.1	0.1	2.2	0.1
Ascomycota _Sordariomycetes _Sordariales _Chaetomiaceae _Chaetomium	0.0	2.1	0.0	0.0	64.2	0.0	0.0	1.4
Ascomycota _Sordariomycetes _Sordariales _Chaetomiaceae _Myriococcum	0.4	1.7	0.0	0.0	0.1	0.0	0.0	0.0
Ascomycota _Sordariomycetes _Sordariales _Sordariaceae _Sordaria	4.1	35.0	1.9	1.9	0.0	0.5	0.1	0.0
Basidiomycota _Agaricomycetes _Auriculariales _Exidiaceae _Exidia	0.4	1.3	0.4	0.4	0.2	0.1	0.0	0.0
Ascomycota; Sordariomycetes; Hypocreales; Hypocreales_Hypocreaceae_Acremonium	2.3	2.5	10.8	20.8	21.3	18.7	10.1	0.9
Zygomycota _Mucoromycotina_Mortierellales_Mortierellaceae_Mortierella	0.0	0.0	0.0	1.3	2.2	73.7	75.0	74.2
No Hit	0.4	1.2	1.2	4.3	4.0	3.1	11.8	10.1
Other[1]	0.2	0.1	0.2	1.6	0.3	0.5	0.2	2.6

[1] Sequences with the abundancy of less than 1%.

APPENDIX E: Chapter 5 Supplementary Data

Total solids test raw data are presented in Table E.1-E.7.

Table E.1. Total solids (TS) of the three main feedstocks at the start-up.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	Aerated OFMSW[1]	32.00	206.66	140.22	62	38	63	37	1
2		30.85	223.11	148.26	61	39			
3		31.82	221.41	154.36	65	35			
4	Digestate	31.80	257.53	145.42	50	50	48	52	3
5		30.87	322.27	158.80	44	56			
6		31.60	324.55	176.89	50	50			

[1] Aerated organic fraction of municipal solid waste with particle size of less than 3/8 inches.

Table E.2. Total solids (TS) of the reactors at day 0 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	C0	15.62	125.39	78.73	57	43	57	43	1
2		15.83	108.04	66.80	55	45			
3		15.70	131.80	82.80	58	42			
4	C20	15.67	132.10	91.54	65	35	65	35	1
5		15.75	108.61	75.83	65	35			
6		15.84	110.68	78.88	66	34			
7	C30	15.76	149.22	93.74	58	42	59	41	1
8		15.67	118.39	76.96	60	40			
9		15.84	98.72	64.95	59	41			
10	C40	15.61	130.61	82.28	58	42	58	42	0
11		15.68	119.20	76.25	59	41			
12		15.72	131.42	91.04	65[1]	35			
13	C50	15.55	136.03	72.86	48	52	49	51	1
14		15.79	135.23	76.34	51	49			
15		15.65	145.35	77.93	48	52			
16	C60	15.83	179.95	105.88	55	45	55	45	0
17		15.64	167.55	99.18	55	45			
18		15.70	137.64	83.28	55	45			
19	C80	3.76	85.68	56.42	64	36	58	42	5
20		3.77	75.43	44.63	57	43			
21		3.72	68.11	37.53	53	47			
22	C100	3.31	62.72	31.35	47	53	48	52	1
23		3.30	49.12	25.91	49	51			
24		3.31	54.66	28.36	49	51			

[1] A piece of ceramic was found in the sample after drying. Therefore, it was not considered in average calculation of TS.

Table E.3. Total solids (TS) of the reactors at day 20 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	C0	15.64	66.00	44.12	57	43	52	48	4
2		15.80	70.42	42.05	48	52			
3		15.73	69.62	42.92	50	50			
4	C20	15.84	61.21	43.43	61	39[1]	54	46	5
5		15.55	56.21	36.86	52	48			
6		15.59	65.86	40.80	50	50			
7	C30	15.71	61.28	40.69	55	45	51	49	3
8		15.76	55.83	35.29	49	51			
9		15.70	55.57	34.85	48	52			
10	C40	15.69	65.30	41.27	52	48	53	47	1
11		15.67	51.35	34.58	53	47			
12		15.83	70.17	45.08	54	46			
13	C50	15.76	50.30	32.13	47	53	46	54	2
14		15.60	54.67	34.19	48	52			
15		15.65	70.57	39.38	43	57			
16	C60	15.66	50.06	31.96	47	53	46	54	2
17		3.78	41.36	20.10	43	57			
18		3.73	37.52	19.27	46	54			
19	C80	15.69	54.47	37.54	56	44	55	51	2
20		3.76	30.76	14.26	39	61[1]			
21		3.31	28.59	16.71	53	47			
22	C100	15.85	65.37	44.92	59%	41	54	46	2
23		3.3	27.48	15.18	49%	51			
24		3.76	37.87	22.16	54%	46			

[1] Contamination was found in the sample after drying. Therefore, it was not considered in the average calculation of TS.

Table E.4. Total solids (TS) of the reactors at day 43 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	C0	15.63	73.28	43.96	49	51	50	50	1
2		15.68	128.74	73.40	51	49			
3		3.30	50.41	26.13	48	52			
4	C20	15.83	105.67	66.12	56	44	56	44	0
5		15.51	108.35	67.46	56	44			
6		3.29	35.70	21.13	55	45			
7	C30	15.67	112.80	64.99	51	49	51	49	1
8		15.60	81.58	50.30	53	47			
9		3.29	31.24	17.39	50	50			
10	C40	15.80	91.24	57.51	55	45	55	45	1
11		15.78	85.23	54.75	56	44			
12		15.69	82.71	52.35	55	45			
13	C50	15.73	89.14	46.96	43	57	47	53	4
14		15.74	77.46	44.04	46	54			
15		3.30	72.75	39.80	53	47			
16	C60	15.67	104.83	55.12	44	5	44	56	1
17		15.64	87.10	46.60	43	57			
18		3.78	37.66	18.91	45	55			
19	C80	15.66	105.56	68.49	59[1]	41	47	53	1
20		15.66	58.46	35.32	46	54			
21		15.66	60.64	37.25	48	52			
22	C100	15.62	94.02	55.76	51	49	53	47	1
23		15.81	65.88	43.27	55	45			
24		3.31	26.80	15.69	53	47			

[1] A piece of metal was found in the sample after drying. Therefore, it was not considered in the average calculation of TS.

Table E.5. Total solids (TS) of the reactors at day 68 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	C0	15.84	94.53	55.42	50	50	49	51	1
2		15.72	82.85	47.80	48	52			
3		15.81	95.12	55.09	50	50			
4	C20	15.72	75.08	50.32	58	42	56	44	2
5		15.64	85.56	54.40	55	45			
6		15.71	85.10	53.43	54	46			
7	C30	15.50	83.81	49.88	50	50	51	49	1
8		15.60	69.51	43.95	53	47			
9		15.57	81.21	48.03	49	51			
10	C40	15.66	84.80	52.68	54	46	54	46	1
11		15.68	78.83	50.61	55	45			
12		15.57	86.82	54.02	54	46			
13	C50	15.73	83.88	47.51	47	53	46	54	1
14		15.66	83.50	46.49	45	55			
15		15.63	90.09	49.36	45	55			
16	C60	15.75	89.57	48.97	45	55	45	55	1
17		15.79	82.56	47.00	47	53			
18		15.77	92.96	50.13	45	55			
19	C80	15.70	73.13	44.57	50	50	49	51	0
20		15.65	60.91	38.05	49	51			
21		15.66	69.29	41.69	49	51			
22	C100	15.68	75.47	47.37	53	47	55	45	1
23		15.53	78.10	50.58	56	44			
24		15.59	67.51	44.33	55	45			

Table E.6. Total solids (TS) of the reactors at day 100 of composting.

Dish ID	Sample ID	Dish weight (g)	Wet weight (g)	Dry weight (g)	TS (%)	MC (%)	Ave TS (%)	Ave MC (%)	STD
1	C0	15.65	75.31	49.71	57	43	57	43	0
2		15.68	85.81	55.21	56	44			
3		15.63	105.63	66.37	56	44			
4	C20	15.78	106.29	66.28	56	44	57	43	1
5		15.74	103.65	64.42	55	45			
6		15.68	92.32	60.50	58	42			
7	C30	15.60	106.34	62.31	51	49	52	48	1
8		15.82	116.12	67.33	51	49			
9		15.51	104.07	62.22	53	47			
10	C40	15.58	103.88	65.35	56	44	56	44	0
11		15.75	112.10	69.71	56	44			
12		15.66	107.55	67.50	56	44			
13	C50	15.72	122.11	66.17	47	53	48	52	0
14		15.67	113.21	62.47	48	52			
15		15.61	106.95	59.37	48	52			
16	C60	15.59	92.45	52.59	48	52	48	52	0
17		15.66	117.53	64.83	48	52			
18		15.72	115.61	64.16	48	52			
19	C80	15.76	111.70	65.67	52	48	52	48	0
20		15.67	124.34	72.35	52	48			
21		15.85	111.95	66.14	52	48			
22	C100	15.70	110.77	69.54	57	43	57	43	0
23		15.80	114.15	71.52	57	43			
24		15.75	121.36	75.71	57	43			

Table E.7. Summary of total solids (TS) of the reactors during composting.

Day	C0	C20	C30	C40	C50	C60	C80	C100
0	57±1	65±1	59±1	58±0	49±1	55±0	58±5	48±1
20	52±4	54±5	51±3	51±1	46±2	46±2	55±2	54±2
43	50±1	56±0	51±1	55±1	47±4	44±1	47±1	53±1
68	49±1	56±2	51±1	54±1	46±1	45±1	49±0	55±1
100	57±0	57±1	52±1	56±0	48±0	48±0	52±0	57±0

Organic matter test raw data are presented in Table E8 to E13.

Table E.8. Organic matter (OM) content of the reactors at day 0 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD
1	C0	85.25	97.22	89.46	65	63	3
2		80.77	92.22	85.34	60		
3		78.25	89.60	82.18	65		
4	C20	69.56	86.16	75.83	62	61	2
5		80.72	97.86	87.96	58		
6		71.81	86.27	77.31	62		
7	C30	77.65	92.79	83.90	59	60	1
8		113.25	130.44	119.99	61		
9		122.71	136.10	128.02	60		
10	C40	115.51	145.08	128.34	57	58	1
11		113.26	144.39	126.14	59		
12		113.56	134.05	122.02	59		
13	C50	125.44	145.33	133.59	59	57	1
14		126.46	150.75	137.12	56		
15		66.82	84.14	74.31	57		
16	C60	69.65	89.89	79.84	50	52	2
17		69.15	90.12	79.32	52		
18		67.78	84.42	75.34	55		
19	C80	71.16	89.82	80.75	49	50	1
20		69.38	85.70	77.39	51		
21		67.89	89.93	78.63	51		
22	C100	67.43	80.59	73.53	54	51	2
23		67.13	82.55	75.19	48		
24		70.63	83.32	76.79	51		

Table E.9. Organic matter (OM) content of the reactors at day 20 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD
1	C0	113.25	122.17	117.18	56	56	1
2		115.49	126.11	120.00	58		
3		122.70	131.55	126.67	55		
4	C20	113.26	123.49	117.75	56	58	2
5		125.44	132.96	128.53	59		
6		113.56	119.80	116.06	60		
7	C30	126.45	133.40	129.29	59	58	1
8		80.72	88.77	84.07	58		
9		85.25	92.87	88.60	56		
10	C40	80.78	91.54	85.39	57	57	0
11		69.56	80.07	74.19	56		
12		78.24	88.05	82.49	57		
13	C50	71.80	79.62	75.18	57	57	1
14		77.65	85.82	81.29	55		
15		70.63	78.63	74.04	57		
16	C60	67.43	75.09	70.77	56	56	0
17		71.16	77.80	74.07	56		
18		67.89	75.07	70.99	57		
19	C80	59.37	65.37	62.18	53	53	2
20		56.97	61.64	59.09	55		
21		56.99	62.99	59.98	50		
22	C100	72.39	80.67	76.83	46	47	1
23		76.17	83.88	80.21	48		
24		75.83	81.67	79.07	45		

Table E.10. Organic matter (OM) content of the reactors at day 43 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD
1	C0	85.25	97.06	90.91	52	53	0
2		78.25	89.79	83.67	53		
3		77.65	92.99	84.90	53		
4	C20	80.72	94.77	87.81	50	51	1
5		80.76	97.96	89.08	52		
6		69.38	81.69	75.45	51		
7	C30	67.42	77.86	72.20	54	54	1
8		67.78	76.54	71.69	55		
9		67.89	78.69	72.92	53		
10	C40	71.20	78.95	74.67	55	52	4
11		67.13	80.78	73.51	53		
12		69.64	81.58	76.07	46		
13	C50	70.19	79.78	74.92	51	51	1
14		69.15	75.90	72.41	52		
15		70.63	82.63	76.62	50		
16	C60	71.16	79.29	74.91	54	54	2
17		68.09	76.12	71.58	57		
18		113.25	123.80	118.31	52		
19	C80	115.51	123.04	118.98	54	53	2
20		125.45	133.35	129.39	50		
21		113.26	126.38	119.13	55		
22	C100	126.45	135.70	131.43	46	47	2
23		113.56	124.60	119.62	45		
24		122.71	133.48	128.22	49		

Table E.11. Organic matter (OM) content of the reactors at day 68 of composting.

Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD
1	C0	71.20	82.10	76.95	47	46	1
2		67.78	79.63	74.29	45		
3		66.82	81.49	74.93	45		
4	C20	113.26	127.40	120.92	46	45	1
5		126.45	146.19	136.99	47		
6		113.25	128.40	121.85	43		
7	C30	125.45	135.99	131.29	45	46	2
8		113.56	124.16	119.38	45		
9		115.51	125.99	120.92	48		
10	C40	67.14	76.66	71.98	49	47	2
11		69.64	80.60	75.79	44		
12		67.89	83.53	76.12	47		
13	C50	71.17	80.32	76.19	45	47	3
14		69.39	78.47	73.88	51		
15		67.42	76.07	72.22	45		
16	C60	68.10	78.09	73.27	48	47	2
17		70.62	82.13	76.99	45		
18		70.19	88.91	79.86	48		
19	C80	69.15	74.71	72.04	48	47	1
20		87.03	97.06	92.54	45		
21		59.19	67.52	63.50	48		
22	C100	71.71	84.54	78.77	45	42	3
23		69.78	85.14	78.73	42		
24		67.89	76.95	73.45	39		

Table E.12. Organic matter (OM) content of the reactors at day 100 of composting.

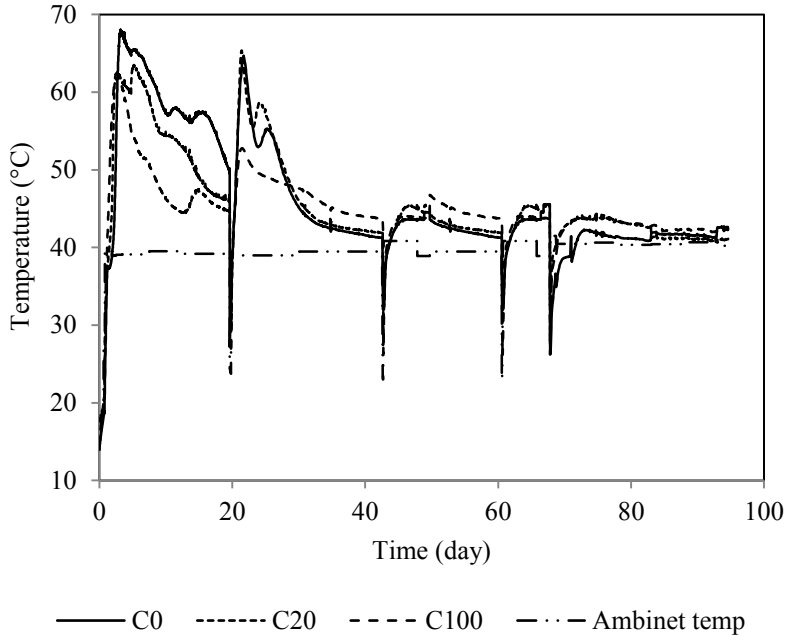
Dish ID	Sample ID	Dish weight (g)	Dry weight (g)	Ash weight (g)	OM (%)	Ave OM (%)	STD
1	C0	113.56	131.02	123.38	44	44	0
2		115.51	130.08	123.74	44		
3		125.44	149.13	138.58	45		
4	C20	113.26	129.46	122.65	42	42	0
5		122.71	138.92	132.15	42		
6		113.25	130.77	123.48	42		
7	C30	126.46	144.86	137.69	39	39	0
8		71.82	88.47	81.9	39		
9		80.74	100.28	92.58	39		
10	C40	80.78	100.46	92.12	42	42	0
11		71.7	92.02	83.51	42		
12		71.17	85.26	79.38	42		
13	C50	70.64	88.75	81.51	40	40	1
14		70.19	85.65	79.57	39		
15		71.25	80.83	76.8	42		
16	C60	66.82	83.01	76.68	39	39	0
17		68.1	85.49	78.83	38		
18		67.89	79.86	75.25	39		
19	C80	69.64	84.26	78.65	38	39	0
20		67.14	80.54	75.29	39		
21		69.16	86.23	79.51	39		
22	C100	67.44	84.68	78.15	38	37	0
23		69.38	85.8	79.76	37		
24		67.78	84.56	78.25	38		

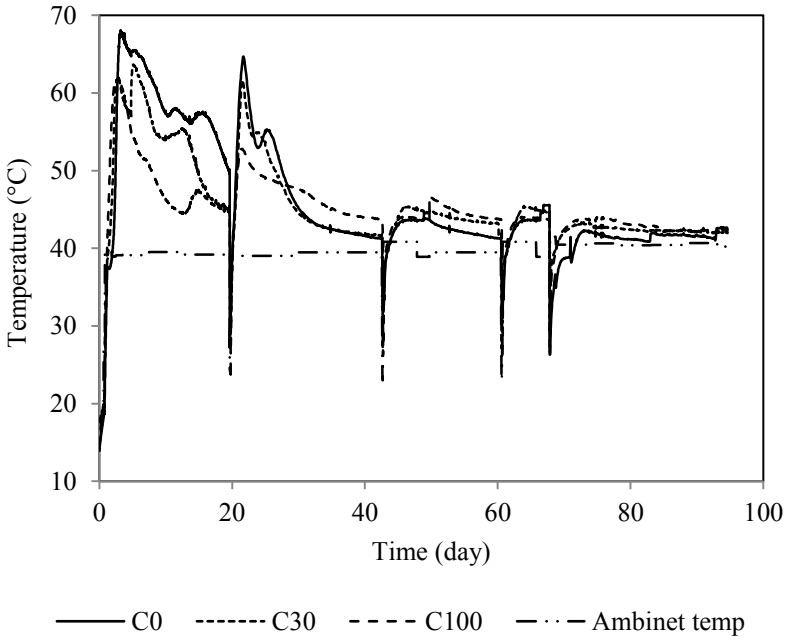
Table E.13. Summary of organic matter (OM) content of reactors during composting.

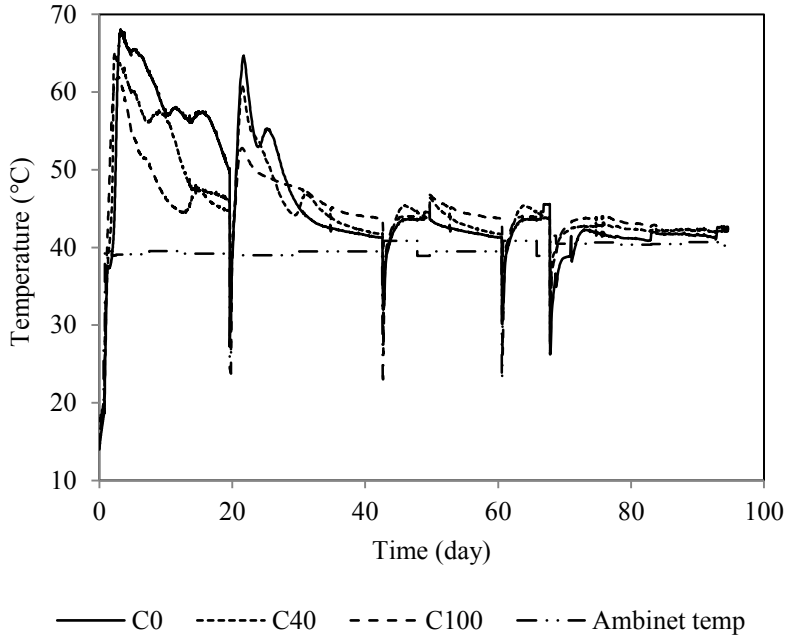
Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	63±3	61±2	60±1	58±1	57±1	52±2	50±1	51±2
20	56±1	58±2	58±1	57±0	57±1	56±0	53±2	47±1
43	53±0	51±1	54±1	52±4	51±1	54±2	53±2	47±2
68	46±1	45±1	46±2	47±2	47±3	47±2	47±1	42±3
100	44±0	42±0	39±0	42±0	40±1	39±0	39±0	37±0

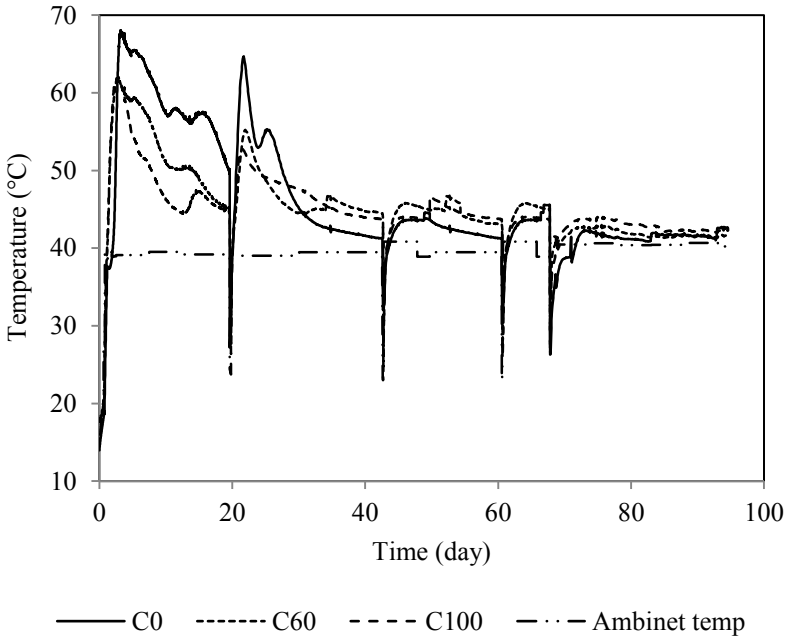
Due to the large volume, the original temperature profiles data and relative heat generation (RHG) calculated from temperature data cannot be presented in the Appendix in their original form. However, the data can be reached from the following link;

http:// goo.gl/xOiPgE






70
60
50
40
30
20
10
Temperature (°C)
0
20
40
60
80
100
Time (day)
C0
C40
C100
Ambinet temp


70
60
50
40
30
20
10
Temperature (°C)
0
20
40
60
80
100
Time (day)
C0
C60
C100
Ambinet temp

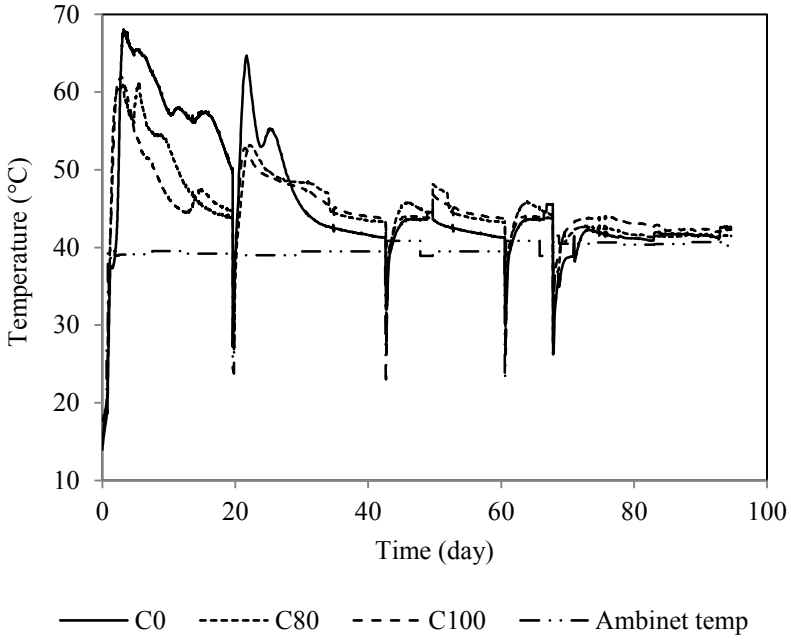
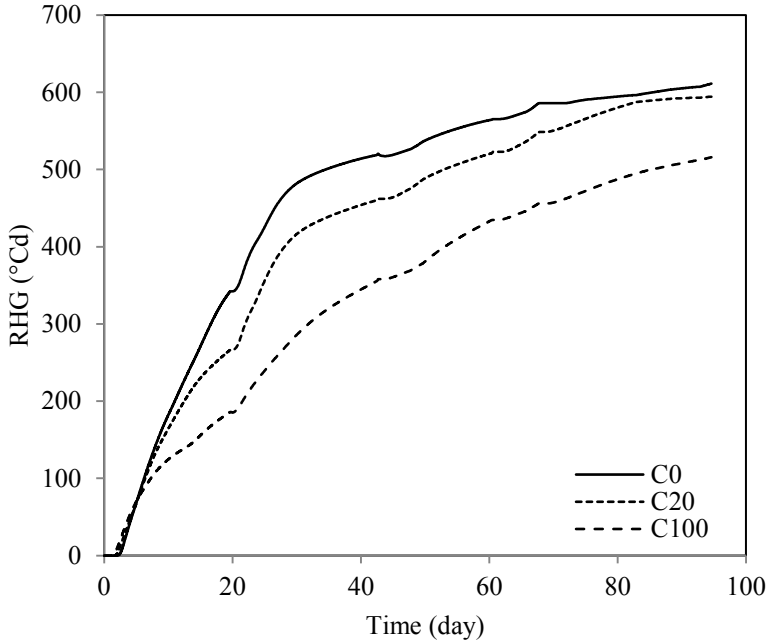
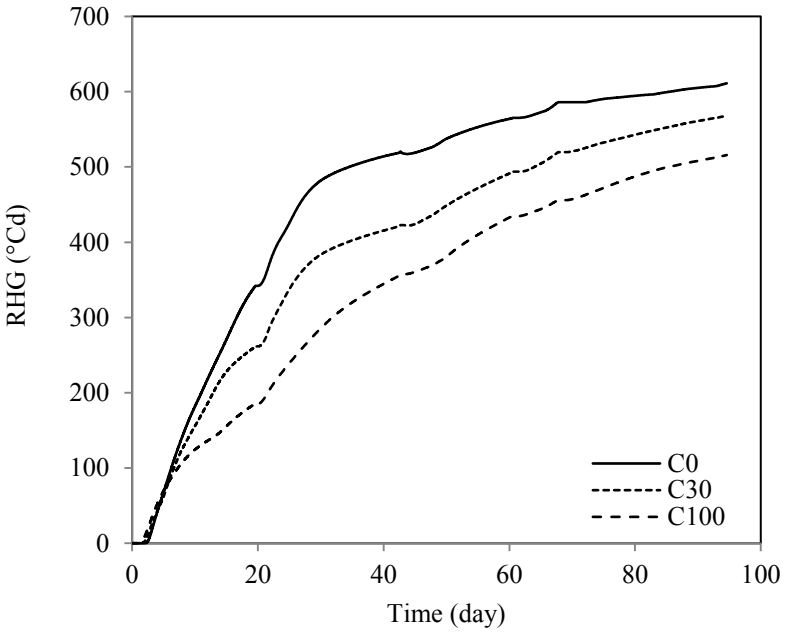
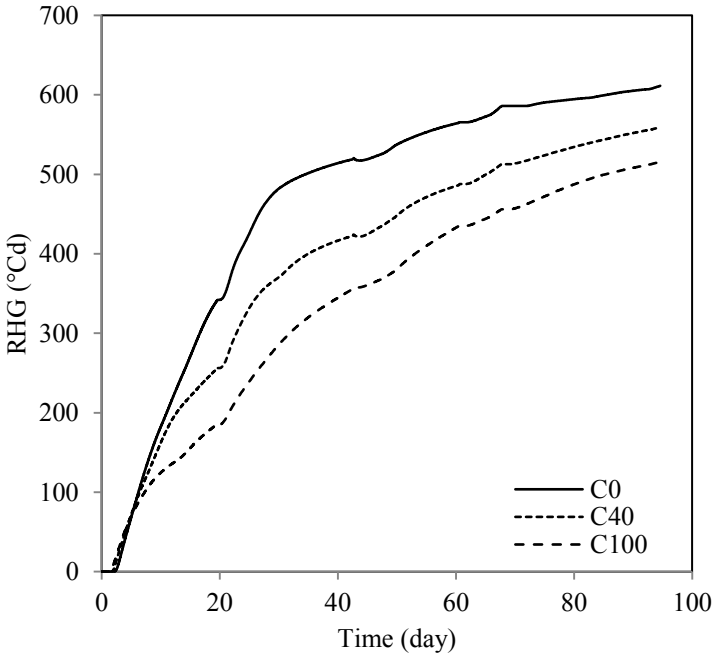
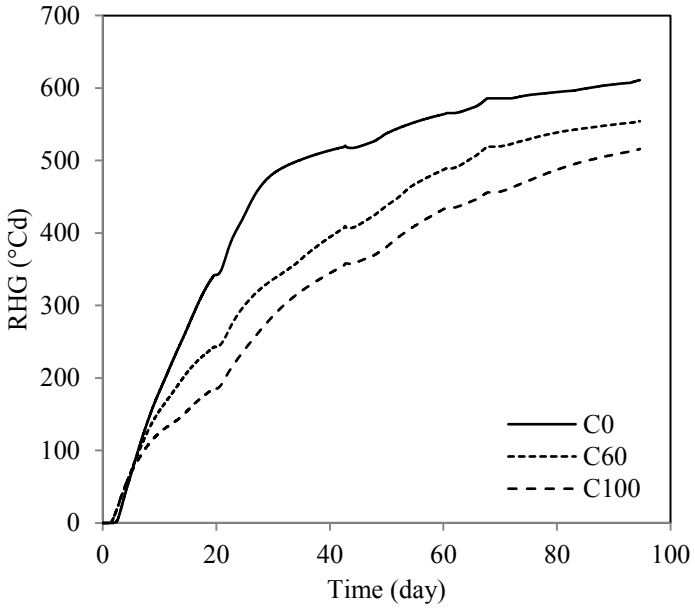


Figure E.1. Temperature evolution during composting.




700
600
500
400
300
200
100
0
RHG (°Cd)
0
20
40
60
80
100
Time (day)
C0
C30
C100


700
600
500
400
300
200
100
0
RHG (°Cd)
0
20
40
60
80
100
Time (day)
C0
C40
C100



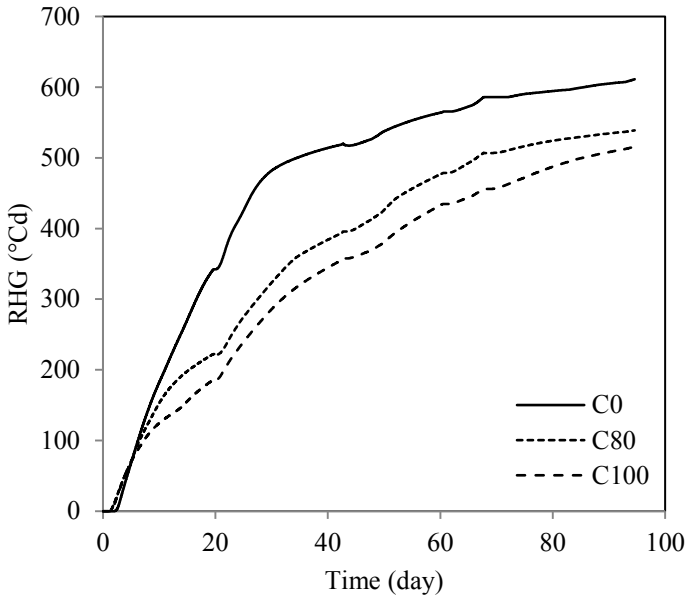


Figure E.2. Relative heat generation (RHG) evolution during composting.

Raw data used to calculate organic matter removal are presented in Table E14-E22.

Table E.14. Organic matter removal in C0 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm[3])	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	13060	56.85	62.73	-	-	-
20	11940	11480	51.69	56.21	1189	1189	255
43	10800	10140	49.55	52.62	519	1709	367
68	9640	9100	49.20	45.68	477	2186	469
100	7500	-	56.61	43.64	192	2378	511

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.15. Organic matter removal in C20 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm[3])	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	11720	65.44	60.65	-	-	-
20	10800	10400	54.46	58.32	1222	1222	263
43	9800	9180	55.66	50.62	542	1764	379
68	8780	8300	56.03	45.22	362	2126	457
100	7900	-	56.55	41.80	235	2361	508

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.16. Organic matter removal in C30 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm[3])	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	11290	59.12	59.95	-	-	-
20	10540	10120	50.53	57.85	920	920	230
43	9680	9040	51.27	54.34	262	1182	295
68	8760	8270	50.79	46.02	471	1653	413
100	7960	-	51.86	39.28	312	1964	491

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.17. Organic matter removal in C40 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm^3)	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	12240	58.24	57.98	-	-	-
20	11060	10620	52.80	56.59	829	829	201
43	9800	9210	55.37	51.54	376	1205	292
68	8680	8180	54.27	46.81	423	1629	394
100	7620	-	56.26	42.00	278	1906	461

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.18. Organic matter removal in C50 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm^3)	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	12740	48.76	57.30	-	-	-
20	10940	10500	46.06	56.53	711	711	200
43	9900	9200	46.98	50.82	370	1081	304
68	8780	8260	45.79	46.73	318	1399	393
100	7880	-	47.77	40.46	245	1643	462

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.19. Organic matter removal in C60 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm^3)	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	12440	55.09	51.91	-	-	-
20	11620	11220	45.60	56.47	566	566	159
43	10620	10000	44.08	54.15	354	920	259
68	9540	9040	45.42	47.08	347	1267	356
100	8660	-	48.30	38.64	317	1584	445

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.20. Organic matter removal in C80 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm[3])	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	11220	57.94	50.27	-	-	-
20	10280	9840	54.67	52.65	308	308	94
43	9180	8500	46.97	53.10	543	851	261
68	8080	7580	49.01	47.12	254	1105	338
100	7240	-	52.24	38.97	276	1382	423

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.21. Organic matter removal in C100 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	OM[2] (%, dm[3])	$OM_{removed}$[4] (g)	Accumulated $OM_{removed}$[5] (g)	ROR[6] (g/kg OM $_{added}$)
0	-	10040	48.44	50.95	-	-	-
20	9220	8800	53.93	46.99	141	141	57
43	8240	7760	52.92	46.70	193	335	135
68	6900	6660	54.79	41.78	338	673	272
100	6300	-	56.69	37.42	188	861	348

[1] Total solids,
[2] Organic matter,
[3] Dry matter,
[4] OM $_{removed}$ at day 20= $Mass_{in}$*TS_{in}*OM (at day 0)- Mass $_{out}$*TS*OM (at day 20).
[5] Accumulated $OM_{removed}$ at day 43= Accumulated OM $_{removed}$ at day 20+ OM $_{removed}$ at day 43.
[6] Relative OM removal (g/kg OM $_{added}$) = Accumulated $OM_{removed}$ / OM added at day 0.

Table E.22. Summary of relative organic matter removal (ROR) during composting (g OM $_{removed}$. Kg^{-1} OM $_{added}$).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
20	255	263	230	201	200	159	94	57
43	367	379	295	292	304	259	261	135
68	469	457	413	394	393	356	338	272
100	511	508	491	461	462	445	423	348

Raw data achieved from respirometry analysis are presented in Table E23-C28.

Table E.23. Specific oxygen uptake rate (SOUR) at day 0 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C20	C30	C40	C50	C60	C80	C100
1	1991.61	2290.40	1623.65	1209.47	1746.83	1545.25	1359.49	1156.42
2	2011.05	2366.43	2023.04	1228.48	1619.07	1420.13	1586.39	1196.68
3	2047.36	2149.52	2404.20	1216.93	1913.08	1545.25	1558.94	1212.92
4	2064.32	2365.28	1967.01	1233.28	1740.54	1420.13	1467.44	1247.67
5	2097.16	2286.86	2401.13	1244.21	1560.50	1243.42	1412.88	1244.23
6	2098.36	2280.70	2333.08	1251.40	1570.43	1758.56	1339.19	1263.26
7	2028.10	2201.99	2259.78	1270.79	1535.82	883.89	1302.21	1259.96
8	2002.86	2150.15	2283.22	1267.57	1510.50	1949.34	1294.52	1235.53
9	2013.88	2098.98	2231.94	1271.37	1328.36	1927.49	1282.52	1263.37
10	2003.23	2074.52	2105.07	1269.29	1485.18	1555.33	1286.00	1245.96
11	1961.30	2034.30	2074.91	1257.22	1426.80	1737.35	1321.84	1256.66
12	1856.92	1950.77	2009.03	1252.90	1420.41	1294.55	1329.20	1237.99
13	1908.11	1925.41	1954.03	1211.63	1422.64	1290.00	1340.57	1233.07
14	2075.53	1864.88	1949.84	1199.12	1386.24	1290.41	1347.47	1195.57
15	2046.95	1843.70	1884.69	1233.28	1349.87	1254.20	1350.71	1194.30
Average	2013.78	2125.59	2100.31	1241.13	1534.42	1474.35	1371.96	1229.57

Table E.24. Specific oxygen uptake rate (SOUR) at day 20 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C20	C30	C40	C50	C60	C80	C100
1	471.24	466.65	478.87	386.39	439.55	455.00	443.47	479.71
2	393.51	412.98	450.48	417.61	428.95	447.79	449.75	468.64
3	414.91	490.94	500.21	421.29	476.49	450.61	479.81	517.93
4	469.29	453.75	458.77	395.70	490.32	438.87	452.74	484.81
5	446.40	424.89	417.78	442.64	454.17	460.82	465.08	502.96
6	414.76	392.89	398.12	416.71	457.59	471.80	455.42	504.69
7	376.09	379.04	413.28	442.31	434.42	461.23	439.40	472.25
8	432.41	352.60	373.78	456.71	468.75	460.15	481.84	514.95
9	444.21	323.59	413.03	415.96	454.89	456.79	468.63	496.80
10	415.23	466.65	433.13	439.71	447.86	457.33	451.87	474.56
11	430.69	412.98	406.79	424.41	504.94	472.65	479.81	489.00
12	439.44	490.94	438.68	468.33	459.44	442.68	456.16	480.72
13	440.85	453.75	392.19	436.55	464.19	447.61	464.78	492.61
14	451.71	424.89	413.47	469.65	473.17	434.03	476.69	507.34
15	384.52	392.89	389.20	430.22	421.69	458.85	427.01	446.69
Average	428.35	422.63	425.19	430.94	458.43	454.41	459.50	488.91

Table E.25. Specific oxygen uptake rate (SOUR) at day 43 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C20	C30	C40	C50	C60	C80	C100
1	154.89	142.41	145.98	150.26	224.76	227.18	283.64	280.72
2	139.49	157.56	150.61	159.58	233.60	219.45	265.41	247.36
3	133.31	151.67	151.10	158.08	231.90	213.26	252.27	232.86
4	148.55	149.50	152.77	152.45	236.74	210.99	251.53	239.67
5	143.32	133.26	148.26	149.41	224.39	214.66	242.25	235.18
6	152.75	139.60	152.99	135.71	224.44	203.16	228.30	216.50
7	146.49	139.45	149.05	151.68	214.01	220.70	230.13	219.52
8	149.58	136.75	155.76	141.99	213.21	186.05	223.49	218.85
9	127.22	139.56	154.24	136.64	202.45	222.59	219.83	207.16
10	138.87	118.49	142.72	149.89	216.94	218.53	211.77	200.84
11	142.58	136.64	151.33	148.84	215.92	218.58	225.49	216.14
12	129.98	124.04	129.39	143.45	195.64	198.04	215.03	216.36
13	131.13	116.54	154.09	142.44	221.57	208.86	206.65	212.54
14	139.37	115.97	144.81	144.55	226.68	223.55	208.56	203.69
15	144.39	120.96	147.01	149.73	226.09	208.52	206.89	199.82
Average	141.46	134.83	148.67	147.65	220.56	212.94	231.42	223.15

Table E.26. Specific oxygen uptake rate (SOUR) at day 68 of composting (mg O_2. Kg^{-1} OM_{added}. h^{-1}).

Interval	C0	C20	C30	C40	C50	C60	C80	C100
1	159.67	111.54	125.94	147.82	172.54	156.07	171.85	162.05
2	169.90	116.59	154.43	141.68	181.14	176.54	170.18	144.11
3	147.89	139.97	182.06	164.81	217.36	134.10	197.83	138.01
4	105.19	125.58	138.20	145.58	172.97	92.25	161.57	137.09
5	156.94	130.43	141.03	140.24	171.32	155.91	164.22	132.84
6	163.39	122.78	127.67	142.32	162.39	176.17	161.69	124.47
7	169.43	107.13	92.51	117.56	138.31	172.16	152.19	111.53
8	152.46	115.01	117.59	144.79	142.75	155.91	153.66	123.90
9	173.43	124.08	121.65	132.08	167.02	172.05	166.34	120.15
10	159.44	128.14	131.09	133.90	184.92	166.17	160.84	127.59
11	164.20	121.24	104.96	123.28	155.64	167.83	136.12	111.67
12	157.46	115.09	111.89	132.76	155.26	164.62	149.99	120.50
13	162.83	110.36	129.49	132.76	166.97	177.29	148.23	113.16
14	154.49	131.10	141.12	144.82	177.69	165.32	174.34	121.46
15	177.06	110.56	113.35	124.84	170.66	183.92	150.56	117.24
Average	158.35	117.95	124.21	134.50	165.21	161.08	157.05	127.05

Table E.27. Specific oxygen uptake rate (SOUR) at day 100 of composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Interval	C0	C20	C30	C40	C50	C60	C80	C100
1	124.85	106.01	101.94	103.56	115.92	124.29	139.55	141.70
2	109.44	106.01	114.29	103.56	122.29	122.18	123.55	133.70
3	129.01	120.88	119.30	121.94	128.94	141.72	134.96	138.03
4	134.37	113.79	113.82	113.07	119.01	113.82	116.56	121.04
5	111.75	113.00	124.84	113.19	117.08	123.33	116.77	125.37
6	125.15	112.24	117.72	110.81	101.73	112.09	113.38	114.20
7	123.37	106.63	115.43	107.57	117.11	96.07	107.53	106.00
8	140.17	115.25	125.34	122.05	116.20	105.46	126.05	118.96
9	132.91	102.81	112.00	112.43	96.44	121.07	112.06	108.97
10	136.96	110.91	118.59	118.82	122.78	103.80	121.64	110.46
11	134.70	97.12	94.20	92.23	88.59	78.90	92.06	84.28
12	140.47	79.76	119.95	114.60	116.73	113.97	123.06	115.19
13	133.19	111.32	120.26	108.77	115.35	105.43	117.64	92.64
14	118.53	80.84	87.27	80.86	75.11	62.44	86.26	75.28
15	126.33	91.11	83.80	86.90	84.79	72.65	92.15	82.69
Average	127.59	104.16	109.58	106.78	107.68	105.33	113.67	109.01

Table E.28. Summary of specific oxygen uptake rate (SOUR) during composting (mg O_2. Kg^{-1} OM $_{added}$. h^{-1}).

Day	C0	C20	C30	C40	C50	C60	C80	C100
0	2014	2126	2100	1241	1534	1474	1372	1230
20	428	423	425	431	458	454	459	489
43	141	135	149	148	221	213	231	223
68	158	118	124	134	165	161	157	127
100	128	104	110	107	108	105	114	109

Raw data achieved from C:N ratio analysis are presented in Table E29-E34.

Table E.29. Carbon content changes during composting (% dry matter).

	Day				
Reactor	0	20	43	68	100
C0-1	31.9	29.0	27.2	24.1	0.2[1]
C0-2	34.0	27.7	26.0	25.9	23.0
C0-3	34.6	29.3	28.1	23.3	22.0
C20-1	30.7	27.1	27.4	24.2	21.8
C20-2	29.7	28.0	27.8	24.0	21.1
C20-3	31.5	30.7	27.6	23.9	21.0
C30-1	31.6	28.7	25.7	22.2	23.1
C30-2	31.3	27.3	24.3	22.9	20.6
C30-3	30.8	27.8	24.6	23.2	21.0
C40-1	31.5	26.9	25.0	23.6	22.0
C40-2	30.8	25.4	23.5	24.5	21.6
C40-3	30.6	27.8	23.6	21.5	22.4
C50-1	30.7	25.2	26.3	23.5	22.3
C50-2	30.3	27.3	24.4	24.8	21.5
C50-3	30.1	28.0	24.5	23.7	22.0
C60-1	29.9	27.3	26.6	25.0	23.8
C60-2	31.9	29.4	28.0	23.3	22.1
C60-3	30.1	27.6	26.4	25.4	22.5
C80-1	27.3	23.6	24.5	22.9	22.8
C80-2	30.1	24.7	24.3	23.2	22.1
C80-3	28.3	25.0	26.2	22.9	21.9
C100-1	32.4	23.4	23.6	21.5	22.9
C100-2	29.8	26.6	22.4	20.3	20.6
C100-3	31.1	25.3	23.6	22.0	21.5

[1] C:N analyzer error.

Table E.30. Summary of carbon content changes during composting (% dry matter).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	33.5±1.2[1]	30.6±0.7	31.2±0.3	31.0±0.4	30.4±0.2	30.6±0.9	28.6±1.2	31.1±1.1
20	28.7±0.7	28.6±1.5	27.9±0.6	26.7±1.0	26.8±1.2	28.1±0.9	24.4±0.6	25.1±1.3
43	27.1±0.9	27.6±0.2	24.9±0.6	24.0±0.7	25.1±0.9	27.0±0.7	25.0±0.9	23.2±0.6
68	24.4±1.1	24.0±0.1	22.8±0.4	23.2±1.3	24.0±0.6	24.6±0.9	23.0±0.1	21.3±0.7
100	22.5±0.5	21.3±0.4	21.6±1.1	22.0±0.3	21.9±1.1	22.8±0.3	22.3±0.3	21.7±0.7

[1] Standard deviation.

Table E.31. Nitrogen content changes during composting (% dry matter).

	Day				
Reactor	0	20	43	68	100
C0-1	2.0	2.4	2.3	2.3	0.1[1]
C0-2	1.9	2.3	2.3	2.4	2.4
C0-3	2.0	2.3	2.2	2.3	2.3
C20-1	2.1	2.2	2.4	2.6	2.5
C20-2	2.0	2.1	2.2	2.6	2.4
C20-3	2.1	2.4	2.2	2.5	2.3
C30-1	2.1	2.0	1.9	2.1	2.2
C30-2	2.1	2.0	2.0	2.0	2.3
C30-3	2.0	2.0	1.9	2.2	2.3
C40-1	1.3	2.2	2.3	2.4	2.4
C40-2	1.6	2.2	2.2	2.4	2.4
C40-3	1.6	2.3	2.1	2.1	2.3
C50-1	1.6	2.0	2.1	1.9	2.3
C50-2	1.7	2.1	2.1	2.1	2.2
C50-3	1.4	2.2	2.2	2.1	2.3
C60-1	1.6	1.9	2.1	1.9	2.1
C60-2	1.3	1.9	2.2	2.0	2.0
C60-3	1.5	1.9	2.1	2.0	2.0
C80-1	1.6	1.8	2.1	2.1	2.5
C80-2	2.1	1.9	2.1	2.1	2.4
C80-3	1.7	2.0	2.1	2.0	2.4
C100-1	1.4	1.7	2.1	1.8	2.3
C100-2	1.5	1.6	2.0	1.9	2.0
C100-3	1.5	1.7	2.1	2.1	2.1

[1] C:N analyzer error.

Table E.32. Summary of nitrogen content changes during composting (% dry matter).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	2.0±0.0[1]	2.1±0.0	2.0±0.1	1.5±0.1	1.6±0.1	1.5±0.1	1.8±0.2	1.5±0.0
20	2.4±0.0	2.2±0.1	2.0±0.0	2.3±0.0	2.1±0.1	1.9±0.0	1.9±0.1	1.7±0.0
43	2.2±0.0	2.3±0.1	1.9±0.1	2.2±0.1	2.1±0.0	2.1±0.1	2.1±0.0	2.1±0.1
68	2.3±0.0	2.6±0.1	2.1±0.0	2.3±0.1	2.1±0.1	2.0±0.1	2.1±0.0	1.9±0.1
100	2.4±0.1	2.4±0.1	2.3±0.0	2.4±0.0	2.3±0.0	2.1±0.1	2.4±0.0	2.1±0.1

[1] Standard deviation.

Table E.33. C:N ratio changes during composting (% dry matter).

	Day				
Reactor	0	20	43	68	100
C0-1	15.9	12.0	12.1	10.6	2.8[1]
C0-2	17.6	11.8	11.5	10.9	9.5
C0-3	17.6	12.5	13.0	10.2	9.6
C20-1	14.9	12.4	11.4	9.4	8.8
C20-2	14.8	13.1	12.5	9.2	8.8
C20-3	15.0	12.9	12.7	9.8	9.0
C30-1	15.3	14.3	13.4	10.8	10.3
C30-2	14.9	13.5	12.1	11.2	8.9
C30-3	15.8	13.7	13.1	10.8	9.0
C40-1	23.8	12.2	10.7	9.9	9.3
C40-2	19.6	11.3	10.7	10.2	9.0
C40-3	18.7	12.0	11.5	10.2	9.6
C50-1	18.6	12.8	12.5	12.2	9.6
C50-2	18.4	13.1	11.6	11.8	9.7
C50-3	21.6	12.8	11.2	11.1	9.4
C60-1	18.4	14.1	12.7	13.1	11.2
C60-2	25.1	15.4	12.7	11.6	11.1
C60-3	20.7	14.8	12.7	12.5	11.0
C80-1	16.9	13.3	11.6	11.1	9.3
C80-2	14.6	12.8	11.4	11.1	9.1
C80-3	16.2	12.8	12.4	11.4	9.1
C100-1	22.5	13.7	11.3	11.8	10.0
C100-2	20.2	16.3	11.5	10.8	10.3
C100-3	20.4	14.6	11.0	10.3	10.2

[1] C:N analyzer error.

Table E.34. Summary of C:N ratio changes during composting (% dry matter).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	17.0±0.8	14.9±0.1	15.3±0.4	20.7±2.3	19.5±1.5	21.4±2.8	15.9±1.0	21.0±1.0
20	12.1±0.3	12.8±0.3	13.8±0.3	11.8±0.4	12.9±0.1	14.7±0.5	13.0±0.2	14.9±1.1
43	12.2±0.6	12.2±0.6	12.9±0.5	11.0±0.4	11.8±0.5	12.7±0.0	11.8±0.4	11.3±0.2
68	10.5±0.3	9.4±0.2	10.9±0.2	10.1±0.1	11.7±0.5	12.4±0.6	11.2±0.1	11.0±0.6
100	9.6±0.0	8.9±0.1	9.4±0.7	9.3±0.3	9.6±0.1	11.1±0.1	9.2±0.1	10.2±0.1

Table E.35. Ammonium nitrogen (NH_4-N) content changes during composting (mg.kg^{-1} DM).

	Day				
Reactor	0	20	43	68	100
C0-1	48	2488	414	165	19
C0-2	67	2490	431	171	19
C20-1	-[a]	70	2289	1510	157
C20-2	-	68	2330	1531	155
C30-1	-	67	1849	1718	156
C30-2	-	63	1820	1669	152
C40-1	-	50	2283	1342	324
C40-2	-	52	2392	1314	327
C50-1	-	90	2319	1542	969
C50-2	-	84	2069	1891	932
C60-1	-	93	1434	1298	1096
C60-2	-	53	1456	1366	1120
C80-1	-	52	1360	1808	1028
C80-2	-	55	1200	1734	1030
C100-1	79	41	87	1825	1147
C100-2	75	44	81	1865	1168

[a] Ammonium content was not measured for this reactor and it was calculated based on the measured values in C0 and C100.

Table E.36. Summary of ammonium nitrogen (NH_4-N) content changes during composting (mg.kg^{-1} DM).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	57±10	61±8	62±7	64±6	66±5	68±3	72±1	77±2
20	2,489±1	69±1	65±2	51±1	87±3	73±20	54±2	43±1
43	422±8	2,309±21	1,835±15	2,337±54	2,194±125	1,445±11	1,280±80	84±3
68	168±3	1,520±11	1,693±24	1,328±14	1,716±175	1,332±34	1,771±37	1,845±20
100	19±0	156±1	154±2	326±2	950±18	1,008±12	1,029±1	1,157±11

Table E.37. Nitrate nitrogen (NO_3-N) content changes during composting (mg.kg^{-1} DM).

	Day				
Reactor	0	20	43	68	100
C0-1	5.8	26.7	40.9	60.1	169.1
C0-2	4.9	25.8	41.3	60.5	174.3
C20-1	-[a]	10.3	48.5	90.1	259.3
C20-2	-	11.6	56.5	92.4	284.0
C30-1	-	9.8	28.0	70.5	153.5
C30-2	-	9.5	26.4	78.7	152.6
C40-1	-	14.8	18.6	45.9	165.4
C40-2	-	12.6	23.5	56.8	166.4
C50-1	-	6.0	22.2	23.0	65.8
C50-2	-	5.5	20.6	23.2	62.7
C60-1	-	93	19.1	23.0	42.1
C60-2	-	53	16.4	27.3	43.0
C80-1	-	52	1.8	3.7	45.2
C80-2	-	55	1.8	3.5	50.3
C100-1	7.2	0.4	2.1	23.9	55.7
C100-2	7.0	0.2	2.4	22.8	41.0

[a] Nitrate content was not measured for this reactor and it was calculated based on the measured values in C0 and C100.

Table E.38. Summary of nitrate nitrogen (NO_3-N) content changes during composting (mg.kg^{-1} DM).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	5.3±0.5	5.6±0.4	5.8±0.4	5.9±0.3	6.1±0.3	6.3±0.3	6.7±0.2	7.1±0.1
20	26.2±0.4	11.0±0.7	9.7±0.2	13.7±1.1	5.8±0.2	3.5±0.2	1.4±0.3	0.3±0.1
43	41.1±0.2	52.5±4.0	27.2±0.8	21.1±2.5	21.4±0.8	17.8±1.3	1.8±0.0	2.2±0.2
68	60.3±0.2	91.2±1.1	74.6±4.1	51.3±5.5	23.1±0.1	25.1±2.1	3.6±0.1	23.4±0.6
100	171.7±2.6	271.6±12.4	153.1±0.5	165.9±0.5	64.3±1.6	42.6±0.4	47.8±2.6	48.3±7.3

Table E.39. pH changes during composting.

	Day				
Reactor	0	20	43	68	100
C0-1	6.7	8.6	8.3	8.2	7.5
C0-2	6.9	8.5	8.0	8.2	7.5
C0-3	6.6	8.3	8.0	8.0	7.4
C20-1	7.8	8.0	8.3	8.6	7.4
C20-2	8.2	7.9	8.2	8.7	7.4
C20-3	7.9	8.0	8.2	8.7	7.4
C30-1	7.6	8.3	8.5	8.6	7.6
C30-2	7.6	8.1	8.3	8.6	7.6
C30-3	7.7	8.1	8.4	8.7	7.6
C40-1	8.4	8.1	8.3	8.6	8.1
C40-2	8.5	7.9	8.2	8.6	8.0
C40-3	8.4	8.0	8.3	8.6	8.0
C50-1	8.1	8.2	8.7	8.7	8.1
C50-2	7.9	8.1	8.7	8.4	8.1
C50-3	8.3	8.1	8.7	8.4	8.0
C60-1	8.5	8.4	8.4	8.8	8.7
C60-2	8.2	8.1	8.4	8.8	8.7
C60-3	8.5	8.2	8.4	8.8	8.6
C80-1	8.6	8.4	8.4	8.5	8.6
C80-2	8.6	8.4	8.2	8.6	8.6
C80-3	8.6	8.3	8.3	8.7	8.1
C100-1	8.3	8.5	8.5	8.8	8.4
C100-2	8.3	8.3	8.3	8.8	8.3
C100-3	8.2	8.3	8.4	8.9	8.4

Table E.40. Summary of pH changes during composting.

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	6.76±0.16	7.98±0.22	7.66±0.06	8.44±0.03	8.08±0.22	8.40±0.17	8.59±0.03	8.26±0.08
20	8.46±0.18	7.94±0.07	8.19±0.09	8.00±0.11	8.15±0.08	8.24±0.17	8.37±0.06	8.38±0.14
43	8.09±0.18	8.24±0.01	8.38±0.11	8.30±0.06	8.70±0.03	8.43±0.01	8.31±0.10	8.38±0.08
68	8.12±0.07	8.64±0.03	8.61±0.06	8.61±0.04	8.48±0.16	8.80±0.01	8.57±0.11	8.83±0.07
100	7.50±0.05	7.39±0.03	7.61±0.03	8.04±0.02	8.06±0.03	8.66±0.04	8.42±0.32	8.37±0.04

Table E.41. Electrical conductivity changes during composting (μS.cm^{-1}).

	Day				
Reactor	0	20	43	68	100
C0-1	2520	827	1048	1217	2420
C0-2	2570	920	1033	1324	2390
C0-3	2450	766	1063	1104	2180
C20-1	2260	1934	2250	1723	2600
C20-2	1374	1452	2480	1596	2340
C20-3	2570	1540	2190	1661	2520
C30-1	1685	1039	1920	1488	2210
C30-2	1982	1218	1711	1358	2080
C30-3	2260	1174	1771	1384	1940
C40-1	1188	1175	1558	1821	2560
C40-2	1438	1262	1987	1794	2540
C40-3	1278	1220	1788	1819	2820
C50-1	1170	1051	1397	1061	1852
C50-2	1580	1053	1103	1058	1771
C50-3	1407	1094	1278	1064	1912
C60-1	1173	1016	1170	1096	1638
C60-2	1170	1151	1190	1100	1587
C60-3	1352	1090	1441	1132	1578
C80-1	1187	1022	1269	1240	1544
C80-2	905	954	1270	1247	1625
C80-3	1180	1098	1443	1150	1688
C100-1	1196	853	1212	1144	1601
C100-2	1145	891	1148	1068	1588
C100-3	1062	819	1144	1078	1563

Table E.42. Summary of electrical conductivity changes during composting (μS.cm^{-1}).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
0	2,513±60	2,068±621	1,976±288	1,301±127	1,386±206	1,232±104	1,091±161	1,134±68
20	838±78	1,496±62	1,144±93	1,219±44	1,066±24	1,086±68	1,025±72	854±36
43	1,048±15	2,307±153	1,801±108	1,778±215	1,259±148	1,267±151	1,327±100	1,168±38
68	1,215±110	1,660±64	1,410±69	1,811±15	1,061±3	1,109±20	1,212±54	1,097±41
100	2,330±131	2,487±133	2,077±135	2,640±156	1,845±71	1,601±32	1,619±72	1,584±19

Table E.43. Carbon removal in C0 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	13060	56.85	33.50	-	-	-
20	11940	11480	51.69	28.67	718	718	289
43	10800	10140	49.55	27.10	251	969	390
68	9640	9100	49.20	24.43	203	1172	471
100	7500	-	56.61	22.50	139	1310	527

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.44. Carbon removal in C20 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	11720	65.44	30.63	-	-	-
20	10800	10400	54.46	28.60	668	668	284
43	9800	9180	55.66	27.60	114	782	333
68	8780	8300	56.03	24.03	228	1010	430
100	7900	-	56.55	21.30	166	1176	500

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.45. Carbon removal in C30 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	11290	59.12	31.23	-	-	-
20	10540	10120	50.53	27.93	597	597	286
43	9680	9040	51.27	24.87	194	791	380
68	8760	8270	50.79	22.77	140	931	447
100	7960	-	51.86	21.57	66	997	478

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.46. Carbon removal in C40 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	12240	58.24	30.97	-	-	-
20	11060	10620	52.80	26.70	648	648	294
43	9800	9210	55.37	24.03	193	841	381
68	8680	8180	54.27	23.20	133	974	441
100	7620	-	56.26	22.00	87	1061	481

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.47. Carbon removal in C50 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	12740	48.76	30.37	-	-	-
20	10940	10500	46.06	26.83	534	534	283
43	9900	9200	46.98	25.07	132	666	353
68	8780	8260	45.79	24.00	119	785	416
100	7880	-	47.77	21.93	82	867	460

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.48. Carbon removal in C60 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	12440	55.09	30.63	-	-	-
20	11620	11220	45.60	28.10	611	611	291
43	10620	10000	44.08	27.00	174	784	374
68	9540	9040	45.42	24.57	126	910	433
100	8660	-	48.30	22.80	55	965	460

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.49. Carbon removal in C80 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	11220	57.94	28.57	-	-	-
20	10280	9840	54.67	24.43	484	484	260
43	9180	8500	46.97	25.00	237	720	388
68	8080	7580	49.01	23.00	87	807	435
100	7240	-	52.24	22.27	12	820	441

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.50. Carbon removal in C100 during composting.

Day	Mass $_{Out}$ (g)	Mass $_{in}$ (g)	TS[1] (%)	C[2] (%, dm[3])	$C_{removed}$[4] (g)	Accumulated $C_{removed}$[5] (g)	RCR[6] (g/kg C_{added})
0	-	10040	48.44	31.10	-	-	-
20	9220	8800	53.93	25.10	265	265	175
43	8240	7760	52.92	23.20	180	444	294
68	6900	6660	54.79	21.27	149	593	392
100	6300	-	56.69	21.67	2	595	393

[1] Total solids,
[2] Carbon,
[3] Dry matter,
[4] C $_{removed}$ @ day 20= $Mass_{in}$*TS_{in}*C (@ day 0)- Mass $_{out}$*TS*C (@ day 20).
[5] Accumulated $C_{removed}$ @ day 43= Accumulated C $_{removed}$ @ day 20+ C $_{removed}$ @ day 43.
[6] Relative carbon removal (g/kg C_{added}) = Accumulated $C_{removed}$ / C added @ day 0.

Table E.51. Summary of accumulated carbon removal during composting (g).

Day	**C0**	**C20**	**C30**	**C40**	**C50**	**C60**	**C80**	**C100**
20	718	668	597	648	534	611	484	265
43	969	782	791	841	666	784	720	444
68	1172	1010	931	974	785	910	807	593
100	1310	1176	997	1061	867	965	820	595

Table E.52. Summary of biodegradable carbon (C_{bio}) during composting (g)[1].

Day	C0	C20	C30	C40	C50	C60	C80	C100
0	1310	1176	997	1061	867	965	820	595
20	592	508	400	412	333	354	336	330
43	341	394	206	219	201	181	99	151
68	139	166	66	87	82	55	12	2
100	0	0	0	0	0	0	0	0

[1]C_{bio} was calculated based on the assumption that all the biodegradable carbon was removed after 100 days of composting. Therefore the initial C_{bio} was equal to the accumulated $C_{removed}$ after 100 days.

Table E.53. Summary of biodegradable carbon (C_{bio}) during composting (%, dm)[1].

Day	C0	C20	C30	C40	C50	C60	C80	C100
0	17.65	15.33	14.93	14.88	13.95	14.08	12.61	12.23
20	9.98	8.98	7.82	7.36	6.88	6.93	6.25	6.96
43	6.79	7.71	4.44	4.30	4.64	4.10	2.49	3.67
68	3.10	3.57	1.57	1.96	2.17	1.34	0.33	0.06
100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[1]C_{bio} (%, dm) @ day 0= C_{bio} (g) @ day 0/ (wet mass (g) *TS (%) @ day0).