URBAN FOOD WASTE COMPOSTING

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ABSTRACT

In this thesis, a study was undertaken on the premise that the world population living in urban centers is expected to increase from 3.8 billion to 5.2 billion, from 2005 to 2025, representing 54% and 65% of total world population, respectively. The urban population (UP) growth will produce remarkable amounts of urban food waste (UFW) that will add more pressure on already overloaded municipal solid waste (MSW) management systems of cities. This problem is more serious in countries experiencing major economic growth such as China where UP is expected to increase from 44% to 66% of the total country population, from 1995 to 2025. Asia produces the largest amount of UFW, which is expected to increase from 251 million ton to 418 million ton (45% to 53% of total world UFW) from 1995 to 2025. On site treatment of UFW along with a limited movement of world population from rural to urban areas are suggested to reduce pressure on MSW management system for the upcoming decades.

In this thesis, a project was also undertaken to develop compost recipes for urban center such as downtown Montreal. Monthly (June to August) average residential FW production was found to 0.61 (+/-0.13) kg capita^{-1} day^{-1} and that of a restaurant was found to be 0.56 (+/-0.23) kg customer^{-1} day^{-1}. From trial tests, the best compost recipes mixed 8.9 kg, 8.6 kg and 7.8 kg of UFW for every kg of wheat straw, hay and wood shaving, on a wet mass basis. However, quantity and characteristics of FW vary from one month to another; therefore, regular adjustment of compost recipe is recommended. When using wood shavings as bulking agent, it is strongly recommended to correct the acid pH.

RESUME

Cette thèse comporte une étude qui prévoit que la population qui occupe les villes du monde (PU) augmentera de 3,8 à 5,2 milliard (de 54 à 65% de population totale mondiale), au cours des prochains 20 ans. Cette croissance fera en sorte que des quantités remarquables de déchets organiques (UFW) devront être géré par les villes alors que plusieurs d’entre elles n’arrivent même pas aujourd’hui à éliminer leurs vidanges. Cette augmentation sera encore plus prononcée chez les pays où on vie un essor économique, comme Chine où l’étude prévoit une augmentation de la PU de 44 à 66%, entre 1995 et 2025. L'Asie produit et continuera à produire la majeure partie des UFW, soit 251 et 481 millions de tonne en ce moment et en 2025, ce qui représente 45 et 53% des UFW produit dans le monde entier. Pour diminuer cette augmentation dans la production des UFW, on pourrait développer des centres de traitements urbains et encourager les gens à rester dans les milieux ruraux où il est beaucoup plus facile de composter et recycler les déchets organiques.

Dans ce contexte, une étude fut entreprise en 2004 pour développer des recettes de compostage pour centres urbains. Premièrement, le projet a mesuré la quantité de UFW produite par un restaurant et par 20 à 48 familles du centre ville de Montréal, ainsi que les propriétés chimiques des UFW produits au cours de l’été par un restaurant et une cuisine communautaire. De plus, le projet a caractérisé six agents structurants disponibles localement, soit de la paille, du foin, des copeaux de bois et trois sortes de cartons. Cette caractérisation a permis de calculer des recettes de compostage et de tester ceux-ci pour déterminer le taux optimum d’humidité. La production de UFW pour le centre ville de Montréal, et pour la population résidentielle fut de 0,61 (+/-0,13) kg par personne et par jour, alors que pour le restaurant, la production fut de 0,56 (+/-0,23) kg par client par jour. Les essais de recettes ont démontré qu’avec tous les agents structurants, 80% d’humidité est idéale, ce qui fait que 8.9, 8.6 et 7.8 kg de UFW peut être composté avec 1kg de paille, de foin ou de copeaux de bois, respectivement. Cependant, la quantité et les caractéristiques des UFW varient d'un mois à l’autre, ce qui exige l’ajustement régulier des recettes de compostage. Aussi, les recettes utilisant uniquement du copeau de bois comme agent structurant doivent être neutralisée.

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AUTHORSHIP AND MANUSCRIPT

This thesis is written in manuscript – based format. The contributions of authors are: 1) first author carried out entire experiment work and writing of manuscripts, 2) second author supervised and technical correction of the work and manuscripts, 3) third author provided technical information and analytical advice.

The authorship of the papers is as follows:

First paper (CHAPTER THREE): B.K. Adhikari, S. Barrington and J. Martinez. This paper has been presented to the journal of "Waste Management & Research" in August 2005.

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ABBREVIATIONS

AF	Animal feed
BA	Bulking agent
C	Carbon
^{0}C	Degree centigrade (temperature scale)
CH	Chopped hay
CH_4	Methane
C/N	Carbon to nitrogen ratio
CO_2	Carbon dioxide
CWS	Chopped wheat straw
d	Day
dw	Dry weight
dwb	Dry weight basis
FW	Food waste
FWPR	Food waste production rate
GDP	Gross domestic product
GGE	Greenhouse gas emission
GUP	Global urban population
h	Hour
H^+	Hydrogen ion
ha	Hectare (measure of area)
HHW	Household waste
Kg	kilo-gram (unit of mass)
kPa	kilo-Pascal (unit of pressure)
MC	Moisture content
MRCB	Medium rough cardboard
MSW	Municipal solid waste
MSWPR	Municipal solid waste production rate
N	Nitrogen
OW	Organic waste

RCB	Rough cardboard
SCB	Smooth cardboard
TKN	Total Kjeldahl nitrogen
TP	Total population
TUP	Total urban population
UFW	Urban food waste
UP	Urban population
VS	Volatile solid
WAS	Water absorption capacity
WBD	Wet bulk density
WP	Wheat pellet
WS	Wood shaving
wwb	Wet weight basis

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Problem statement

From 1950 to 2000, the global urban population (GUP) has increased from 0.8 billion to 2.9 billion and by 2030, it is expected to reach 5 billion (World urban prospects 2002). In 1950, the GUP represented 30% of the total world population, in 2000 it represented 47 % and in 2030 it will represent an even higher level of 60%.

This ever-increasing shift of the world population towards urban centers is already evident and will produce even more remarkable amounts of urban food waste (UFW), which in turn will add pressure to the already over-loaded municipal solid waste (MSW) transportation system and landfill sites. The environmental ramifications of widely used waste disposal technologies are well-understood (Bilitewski et al 1994, Barth 1999). Organic solid waste that goes to landfill sites pollutes air by producing large amounts of methane (CH_4)) and carbon dioxide (CO_2) (Hansen et al 2004). Also contaminates groundwater by producing important volumes of leachate and occupies vast land surfaces (Pokhrel & Viraraghavan 2005, Bou-Zeid & El-Fadel 2004, Shin et al 2001, Legg 1990). Food waste (FW) is a major fraction of MSW, which is a main source of decay, odor and leachate when collected, transported and landfilled together with other wastes (Shin et al 2001).

The treatment and disposal of MSW is a worldwide concern especially in highly urbanized cities (Lu 1995). Large cities in India and China are faced with a serious solid waste problem, which is further aggravated by rapid urbanization (Ahmed & Jamwal 2000, Hong et al 1996). In most cities of low and medium income countries do not collect the totality of wastes generated; and, of the wastes collected, only a fraction receives proper disposal. For example, India, Pakistan (Karachi) and Egypt (Cairo) only 50%, 33% and 50% of refuse generated is collected respectively and rest is left behind (Sinha & Enayetullah 1995, Medina 2002). About 90% of MSW collected in Asian cities end up in open dumps (Medina 2002) and in African countries only 20 – 80 percent of the waste are collected. Uncollected or illegally dumped wastes adversely affect human health and the environment (Achankeng 2003). Uncollected waste may accumulate on the streets and clog drains when it rains, which may cause flooding and wastes can also be carried away by run off water to rivers, lakes and seas, and affecting those ecosystems (Medina 2002, Chakrabarti & Sarkhel 2003).

According to 1997 survey about 93% of Chinese felt their health was affected by environmental problems resulting from poor MSW management (China Waste Management 2004). In India, this case is even higher which is 94% (World Bank 1999:16). An example of human disaster is a case of outbreak of plague in Surat, India in September 1994. Which took the life of many people because of uncontrolled fermentation of organic waste that created conditions favorable to be breeding and growth of rats and insects that acted as vectors of disease (Venkateshwaram 1994). Similar cases of serious impact on health and environment is reported in Nepal resulting from open dumps in abandoned fields or on the bank of rivers or streams ranging from 65% – 100% of the MSW depending on the municipalities (Pokhrel & Viraraghavan 2005).

In this context, on site treatment, aerobic and anaerobic, of FW reduces pressure on MSW management systems about 40% to 85% in developing economies and 23% to 50% in developed economy (World Bank 1999, OECD 1995).

Composting of source-separated FW at urban centers reduces the mass and volume transported to the landfill and increases its life (Pokhrel & Viraraghavan 2005). This has been the trend since mid 1980s (Bilitewski et al 1994, Hoitink 1999, Barth 1999). Currently, yard waste composting is practiced widely and also food and restaurant waste composting is increasing (Hoitink 1999). Composting of FW in city itself rather than outside the city reduces the transportation cost of MSW management system because large city corporations already have serious problems transporting the waste outside the city.

However, there are many challenges in building and operating composting facilities in highly urbanized centers. The composing facility must be compact as to use as little space as possible. The FW needs to be mixed to a readily available bulking agent to reduce its moisture content and facilitate composting, and this bulking agent may not be readily available. Cooperation and involvement of communities who produce waste are vital to operate urban composting facilities successfully. Finally, the odors and leachate produced by the composting process require special attention especially in the case of composting facilities installed in a highly populated urban setting.

1.2 Objectives

The main objective of this research was to develop guidelines for an urban composting center for the on-site treatment of source-separated FW and for its reuse by the compost producer. This urban system can thereby reduce the volume of MSW delivering to landfill sites and consequently attenuate the adverse environmental impact resulting from bio-urban solid waste.

The specific objectives were to:

(i) Predict the growth of urban population (UP) and UFW production in relation with gross domestic product (GDP) in continental and global scale.

(ii) Characterize the properties of Montreal FW and various readily available materials which could be used as bulking agents in compost recipes.

(iii) Test compost recipes to measure temperature, pH and identify the best for UFW composting using a compact urban composting system.

1.3 Scope

The growth of UFW was quantified in continental and global scale in relation with urban population and GDP. The properties (which are needed for compost recipe) of Montreal community kitchen & restaurant FW also locally available bulking agents were characterized. The different mixtures of FW & chopped wheat straw, FW & chopped hay and FW & wood shaving were tested to obtain best recipes by using an urban composting unit prototype for a compact urban composting system designed to treat FW.

1.4 Layout of thesis

Chapter 2 presents a general literature review covering the topics of urbanization & waste production, impact on environment, composting and factors to be taken into consideration for composting process. Chapter 3 is a paper presenting the predicted growth of FW in continental and global scale in urban areas. Chapter 4 is a paper pertaining to characterization of properties of UFW and bulking agents needed for preparation and test of compost recipes. Chapter 5 is a paper discussing tests of compost recipes by using composting unit prototype for a compact urban composting system designed to treat FW. Chapter 6 is the general conclusion. Tables and figures are depicted in sequence at the end of each chapter. The literature cited within a chapter is presented at the end of each chapter.

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CHAPTER TWO
LITERATURE REVIEW

2.1 Urbanization and food waste production

2.1.1 Urban population (UP)

According to World Urbanization Prospects (2002), the global urban population (GUP) in 1950, 1975 and 2000 was about 0.8 (30% of total), 1.6 (38% of total) and 3 (47% of total) billion, respectively, and is expected to reach about 5 (60% of total) billion in 2030. Also, the urban areas are expected to absorb most of the world population (WP) increase from 2000 to 2030, and this is particularly true for the countries in Asia, Africa, Latin America & the Caribbean. From 1950 to 2030, the UP is expected to increase from 17% to 54%, 14% to 53% and 42% to 84% in Asia, Africa and Latin America & Caribbean, respectively. In comparison, the UP of the more developed countries in Northern America, Europe and Oceania is expected to increase slowly from 64% to 85%, 52% to 81% and 62% to 76% respectively from 2000 to 2030. The increasing trend of UP and expansion of urban areas over the period of time will produce tremendous amounts of waste in city centers. That will create heavy pressure in municipal solid waste (MSW) management systems.

2.1.2 Urban food waste (UFW) production

The production and composition of MSW vary from place to place and from season to season (Abu Qdais et al 1997). Which is influenced by various factors such as geographical location, population's standard of living, energy source, weather (World Bank 1999), food habits, urbanization, tradition and culture. In general, the greater the economic prosperity and the higher percentage of UP, the greater amount of solid waste produced (World Bank 1999). Medina (2002) found a positive correlation between income and amount of solid waste production because wealthier countries and individuals consume more than lower income one, which results in a higher waste generation rate to the former. For an example, as reported by China Waste Management (2004), during the last two decades the economic growth rate of China is of almost 10% that is increasing the living standard and consumption pattern of UP. That increases the total amount of MSW generation at similar pace of 8% – 10% annually.

Table 2.1 shows an average rate of MSW generation corresponding to income level of different countries across the world. Countries with low income produce fewer amounts per capita per day in comparison to countries having high income. In 1990, the average MSW production rate in low income countries was reported as 0.53 kg $capita^{-1}day^{-1}$, in the case of middle income countries it ranges from 0.63 to 0.71 kg $capita^{-1}day^{-1}$ whereas high income countries produced 1.2 kg $capita^{-1}day^{-1}$ in same year.

Compostable materials in comparison to high and middle-income countries mostly dominate the MSW stream in low-income countries. Low and middle income countries have a high percentage of compostable or organic matter in the MSW stream which ranges from 40% to 85% whereas in high income countries it is significantly lower which ranges from 23% to 50% (Table 2.2 & 2.3). The consumption of papers and packaging materials in MSW stream increases with growing urbanization and income level of the country (Table 2.2 & 2.3). The percentage of food waste (FW) in MSW is reported as 39.2%, 62.5%, 60%, 43.1% and 8.1% in Bangkok (1989), Dar es Salaam (1988), Jakarta (1989), Mexico City (1980) and United States (1990) respectively (Beed & Bloom 1995). The percentage of FW in MSW in US is reported as low as 8.1% due to source reduction of FW by composting that prevents mixing with MSW stream (USEPA web site). This is true because the percentage of FW in residential waste production in US is reported 27% (Table 2.4).

Percentage of organic waste (OW) and FW of different cities and countries across the world in Residential/household waste stream are presented in Table 2.4 & 2.5. These Tables demonstrate higher percentage of OW and FW in cities/countries having low income and low urbanization with lesser per capita residential/household waste production in comparison to high-income countries. Another study in Canada and USA shows that the percentage of yard and FW ranges 22% to 32.2 % in domestic waste stream in British Columbia, Ontario and Quebec and in USA it is reported 25% (Table 2.6). On an average OW comprises approximately 30% of the residential wastes produced in Canada (The Recycling Council of Ontario, 1997). A study in Montreal revealed that the residential FW production rate varies from 0.5 to 0.7 kg $capita^{-1}day^{-1}$ (Morin et al 2003). Assuming the FW production rate of 2003 as reported by Morin et al (2003), the total population of Montreal 1,040,000 (Statistics Canada 2001) produced about 0.23 million ton FW. Which is about 36% of total domestic waste produced in Montreal by considering country domestic waste production rate 1.7 kg capita^{-1}day^{-1} (Environment Canada 1991, Laplante 1992).

2.2 Impact on environment

According to Bilitewski et al (1994), the link between hygiene, wastes and epidemics was first suspected by the Greek scholar Hippocrats around 400 B.C. and the Arab Avicenna (Ibn Sina, 1000 AD). Early in the 20th century, urban societies began to grow and to have a noticeable impact on the environment because of the increasing amount of urban waste and wastewater produced (Green & Kramer 1997). At present world, the potentially damaging impacts of farm and FW on the local environment like water pollution and human health are well recognized (Legg 1990).

The UFW that goes to landfill sites not only pollute the land and water but also contributes to global warming by producing methane (CH_4). CH_4 is produced in large amounts in landfills as a consequence of the degradation of organic matter (OM) under anaerobic conditions (Borjesson & Svenssen 1997). At any landfill site, 45% to 58% of the OW on a dry weight basis (dwb) is transformed into CH_4 (Solid Waste Landfill Guidance 1999). Food waste fraction of MSW has high potential to produce CH_4 (Table 2.7). According to Wang et al (1997), FW generates 300 L of CH_4 dry^{-1} kg. Thus, landfills are responsible for approximately 8% of anthropogenic world CH_4 emissions (US EPA 1994). Another laboratory experiment conducted by Hansen et al (2004) found that solid FW could produce from 200 to 500 L of CH_4 kg^{-1} of FW volatile solids (VS).

Although CH_4 and CO_2 are produced in about equal amounts, CH_4 is of greater concern as a greenhouse gas because of its 100 years global warming potential. For example, its infrared absorption potential in the atmosphere is about 23 times greater than that of CO_2 (IPCC 2001). In 1997, the US landfills are said to contribute 37% of the anthropogenic CH_4 that represents the largest fraction of all the anthropogenic sources (USEPA 2003). In Europe, an estimated 30% of anthropogenic CH_4 emissions are from landfill sites (EEA 2001).

2.3 Reuse of UFW

Waste management encompasses the collection, transport, storage, treatment, recovery and disposal of waste (Bilitewski et al 1994). Multiple waste management alternatives exist for the treatment of UFW including burial in a landfill, anaerobic digestion (Ten Brummeler & Koster 1989, Cecchi et al 1992) and aerobic composting. The greenhouse gas emission potential and cost effectiveness of all of these techniques must be evaluated to select the most environmentally friendly treatment system.

Amongst the many available alternatives for reusing of UFW, composting is envisaged as the best way of disposal of FW by using it on the land as organic fertilizer (Pokhrel & Viraraghavan 2005). Because composting process transforms OM into a stable form (Hamelers 1992). Composting of FW not only reduces the waste mass and volume transported to the landfill also increases its life (Pokhrel & Viraraghavan 2005). Invessel treatment of MSW waste avoids air and groundwater pollution by landfills (Baeten & Verstraete 1992). Also recycling of source-separated FW by composting at the urban community centers and in large scale FW composting facilities reduce CH_4 emissions and saves land otherwise needed for landfill sites.

2.4 Composting of FW

Composting is one of the few natural processes (Barrington et al 2002) in which, microbial decomposition of OM occurs in aerobic conditions. Composting generates considerable heat, CO_2 and water vapor into the air while minerals and OM are converted into a potentially reusable soil amendment (Renkow et al 1996, Pace et al 1995, Biddestone & Gray 1985, Picci et al 1978, Haug 1980). Composting also reduces volume and mass of solid waste, thereby increasing its value and transforming it into a safe soil amendment (Cassarino 1986).

As reported by Renkown et al (1996), the two basic processes used in large scale composting are windrow-based technologies and in-vessel technologies. The invessel technologies are considered appropriate for UFW composting because the process can be fully controlled and at the same time leachate and odor can be collected and treated before discharging in to the atmosphere which is specially important for urban composting centers. In vessel composting of FW were successfully carried out by using wood chip and sawdust (Kwon & Lee 2004) and peat moss and wood chips (Koivula et al 2003) as bulking agents.

2.5 Factors affecting the composting process

Various factors affect the composting processes and determine the level of biological activities. The main factors are moisture, temperature, pH, initial recipe C/N ratio and oxygen (Pace et al 1995, Zucconi et al 1986).

2.5.1 Moisture

The FW and bulking agent mixture should have an initial moisture level of 60- 65% (Zucconi et al 1986). According to Pace et al (1995), the composting mixtures should be maintained within a range of 40% to 65% moisture and preferably 50%- 60%.

The raw compost mixture should have water content of approximately 55% because microbes absorb nutrients in molecularly dissolved form through a semi permeable membrane. At a moisture content under 20%, no biological processes are possible (Bilitewski et al 1994). According to Haug (1980), McGauhey & Gotaas were able to compost mixtures of vegetable trimmings at initial maximum moisture contents as high as 85% when using straw as bulking agent, and 76% when using paper. Fibrous or bulky material such as straw or wood chips can absorb relatively large quantities of water and still maintain their structural integrity and porosity (Haug 1980). Therefore, higher moisture levels are recommended for bulky and fibrous composting material (Table 2.8).

2.5.2 Temperature

Temperature is generally a good indicator of the biological activity. Thermophilic temperatures above 50°C should be reached within a few days. Temperature above 60°C -65°C should be prevented because the more sensitive microorganisms may be killed and the decomposition process may be slowed. Nevertheless, a continuing high temperature of 55°C -60°C, lasting beyond 5 to 6 weeks, indicates an abnormally prolonged decomposition and a delayed transition to the stabilization stage (Zucconi et al 1986). Composting will essentially take place within two temperature ranges known as mesophilic (25°C to 40°C) and thermophilic (over 40°C). Although mesophilic temperatures allow effective composting, experts suggest maintaining thermophilic ranging up to 60°C, because they destroy pathogens, weed seeds and fly larvae (Pace et al 1995).

2.5.3 pH

For optimum microbial activity during composting, a neutral to slightly alkaline pH range is required (Table 2.9) for optimal microbial growth. Organic substrates offer a wide range of pH levels ranging from 3 to 11 and this pH must be neutralized (Zucconi et al 1986). Generally, the pH level drops at the beginning of the composting process as a result of the acids formed by the acid-forming bacteria which initialize the process by breaking down complex carbonaceous materials. The later break down of proteins and liberation of ammonia account for the subsequent rise in pH (Zucconi et al 1986, Bilitewski et al 1994). According to Pace et al (1995), the preferred range of pH is 6.5 to 8.0. Table 2.9 demonstrates the ranges of pH for optimum growth of microorganisms during composting process as suggested by various researchers.

2.5.4 C/N ratio

The C/N ratio insures the necessary nutrients for the synthesis of cellular components of microorganisms. For an active aerobic metabolism, a C/N ratio of 15 to 30 is suggested (Haug 1993). Zucconi et al (1986) suggested that the C/N ratio of the microbial cell be about 10. However, due to energy requirement, initial C/N values of 28-30 maximize metabolic rates. According to Pace et al (1995), raw materials blended to provide a C/N ratios of 25 to 30 are ideal for active composting although initial C/N ratios of 20 to 40 consistently give good composting results. A C/N ratio below 20 produces excess ammonia and unpleasant odors while a C/N ratio above 40 does not provide enough N for microbial growth and a fast composting process.

Once completely composted, the treated waste should offer a C/N ratio ranging between 15 and 20, to be used as a balanced soil amendment. If the C/N ratio exceeds 20, N becomes deficient in the soil, and if the ratio is significantly below 15, N can be lost by volatilization from the soil and can have a toxic effect on plants (Bilitewski et al 1994)

2.5.5 Aeration

Aerobic microorganisms should dominate during the composting process and oxygen is of major consideration (Finstein et al 1992). According to Barrington et al (2002) aeration is a key element in controlling the temperature regime and thus, the performance of any composting operation.

Fernandes et al (1994) suggested three types of aeration techniques for composting: natural, passive and active. Among these three methods, natural aeration is the cheapest and simplest, as it requires no installations. It consists of ensuring enough compost pile surface to allow for the proper exchange of oxygen by diffusion. Passive aeration requires the installation of ducts under the compost plies to enhance the convective forces created by the temperature differences between the composting materials and the ambient air (Sartaj et al 1997). Active aeration is the most expansive system, as it requires the installation of ducts under the compost piles and fans pushing air into these ducts and through the compost piles (Haug 1993).

Oxygen demand is very high during the initial decomposition stage, because of the rapidly expanding microbial population and the high rate of biochemical activity. After this initial high level of activity that generally lasts one to two weeks, oxygen demand decreases (Zucconi et al 1986).

2.6 Emissions during composting

Composting leads to the emissions of malodors and leachate that require special attention. These may occur during the delivery and handling of the raw materials and during the composting processes (Bilitewski et al 1994).

Odor can be attenuated by optimizing the composting process to minimize the formation of odor and by collecting, treating and disposing the odorous gases which are formed (Walker 1992). The leachate can be collected, treated and disposed or returned to the composting process (Bilitewski et al 1994). Recently, the leachate has been recycled as a liquid fertilizer, because of its high content in soluble minerals.

2.7 Characteristics of waste and bulking agents

Determination of various waste characteristics is essential for implementing the appropriate waste management practices (Green & Kramer 1979, Metin et al 2003, Abu Qdais et al 1997). Therefore, waste and bulking agent characterization is essential for the optimization of the composting process. The nutrient content of various composting substrates is presented in Tables 2.10 and 2.11. Materials like saw dusts, wood chips and straws indicate high dry matter and C/N ratio which show the suitability for using as bulking agents during composting of FW. (Table 2.11).

2.8 Conclusion

The growing urbanization, economic activities and changing consumption pattern (will) create tremendous pressure on existing MSW management systems by producing remarkable amount of FW in big cities around the world specially in low and middle income countries. However, no literature is available about future growth of UFW in the context of growing urbanization and changing economic pattern; which is an important part to formulate MSW management strategy for upcoming decades.

For managing and reusing of FW (solid organic fraction of MSW stream), various alternatives are suggested such as burial in a landfill, anaerobic digestion and aerobic composting. Amongst the available alternatives, composting at urban centers is envisaged as the best option. However, there are many challenges in building and operating composting facilities in highly urbanized centers like availability of space and bulking agents. The odors and leachate produced by the composting process require special attention especially in the case of composting facilities installed in a highly populated urban setting. Therefore, factors affecting composting process such as moisture, temperature, pH and initial C/N ratio of compost recipe need to be fully controlled in order to accelerate the process with minimal odor emission and less leachate production. Hence, quantification, characterization of both FW and bulking agents are essential to obtain best compost recipes to control the composting process.

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Table 2.1 MSW generation of different economic group countries (1990)

Income group	[1]GDP capita^{-1}year^{-1} (US $)	[2]MSW generation rate (kg capita^{-1}day^{-1})
Low	< 1500	0.53
Lower-middle	1500 – 3000	0.63
Upper-middle	3000 – 10000	0.71
High	> 10000	1.20

Reference: [1]UN Statistics Division, [2]Beede & Bloom (1995)

Table 2.2 Changes in the MSW composition with economic prosperity

Countries	Components (%)					
	Compostable or organic	Paper	Plastic	Glass	Metal	Others
Low-income						
Nepal (1994)	80	7	2.5	3	0.5	7
Bangladesh (1992)	84.37	5.68	1.74	3.19	3.19	1.83
Lao PDR (1998)	54.3	3.3	7.8	8.5	3.8	22.5
Sri Lanka (1993-94)	76.4	10.6	5.7	1.3	1.3	4.7
China (1991-95)	35.8	3.7	3.8	2	0.3	54.3
Myanmar (1993)	80	4	2	0	0	14
India (1995)	41.8	5.7	3.9	2.1	1.9	44.6
Middle-income						
Thailand (1995-96)	48.6	14.6	13.9	5.1	3.6	14.2
Malaysia (1990)	43.2	23.7	11.2	3.2	4.2	14.5
Mexico (1993)[a]	52	14	4	6	3	20
Turkey (1993)[a]	64	6	3	2	1	24
Indonesia (1993)	70.2	10.9	8.7	1.7	1.8	6.2
Philippines (1995)	41.6	19.5	13.8	2.5	4.8	17.9
High-income						
Canada (1993)[a]	34	28	11	7	8	13
USA (1993)[a]	23	38	9	7	8	16
Australia (1993)[a]	50	22	7	9	5	8
Denmark (1993)[a]	37	30	7	6	3	17
Finland (1993)[a]	32	26	0	6	3	35
France (1993)[a]	25	30	10	12	6	17
Greece (1993)[a]	49	20	9	5	5	13
Netherlands (1993)[a]	43	27	9	4	5	8
Norway (1993)[a]	18	31	6	4	5	36
Spain (1993)[a]	44	21	11	7	4	13
Switzerland (1993)[a]	27	28	15	3	3	24
Japan (1993)	26	46	9	7	8	12
Hong Kong (1995)	37.2	21.6	15.7	3.9	3.9	17.6

Reference: World Bank (1999), [a]OECD (1995)

Table 2.3 City and country wise MSW generation and component of putrescibles

City/country	GDPcapita^{-1}* (1994 in US$) & %UP in1985**	MSW (kg capita^{-1}day^{-1})	%Putrescible (ww)	%FW (ww)
Nepal	212 & 7.8	0.25–0.5[a]	≥70[a]	-
India	373 & 24.3	0.15-0.8[a1]	40-85[b]	-
La paz, Bolivia	878 & 50.5	0.5[c]	53.5[c]	-
Sasha Settlement, Nigeria	909 & 30.7	0.17[c]	76[c]	-
Manila, Philippines	1058 & 43.1	0.42[c]	49.8[c]	-
Asuncion, Paraguay	1832 & 45	0.64[c]	60.8[c]	-
Lima, Peru	2109 & 66.9	0.96[c]	34.3[c]	-
Turkey	2536 & 52.5	0.95[d]	50-55[d]	-
Bangkok, Thailand	2619 & 17.9	0.93[e]	-	23-44[f]
Rio de Janeiro, Brazil	2634 & 70.7	0.54[c]	47.7[c]	-
Mexico city, Mexico	3412 & 69.6	0.68[c]	56.4[c]	-
Caracas, Venezuela	3477 & 81.9	0.94[c]	40.4[c]	-
USA	27678 & 74.5	1.8[g]	6.7-13.2[h]/6-18[i]	-

GDP capita^{-1}: gross domestic product per capita
%UP: percent urban population
ww: wet weight
Reference: *IEA (2002), **UNCHS (2005), [a]Pokhrel & Viraraghavan (2005), [a1] Shekdar (1997), [b]National Solid Waste Association of India (2003), [c]Diaz et al (1986), [d]Metin et al (2003), [e]ESCAP (1990), [f]Muttamara et al (1994), [g]USEPA (1992), [h]Lober (1996), [i]USEPA (1994), [i]Tchobanoglous et al (1993)

Table 2.4 Residential waste production (RWP)

City/country	GDPcapita^{-1}* (1994 in US$) & %UP in1985**	RWP (kg capita^{-1}day^{-1})	%FW (ww)
India	373 & 24.3	0.41	-
Saudi Arabia	6887 & 72.7	-	35
Quatar	14643 & 87.9	-	53.3
Kuwait	15055 & 93.8	1.51	37.5
Abu Dhabi, UAE	16035 & 76.9	1.76[a]	49[a]
UK	19187 & 88.9	0.8	28
USA	27678 & 74.5	1.98	27
Germany	29717 & 84	1.15	-

Reference: *IEA (2002), **UNCHS (2005), [a]Abu Qdais et al (1997), Ward (1993)

Table 2.5 Household waste (HHW) and MSW production in European cities

City/country	HHW kg $res^{-1}day^{-1}$	%OM (by mass)	MSW kg $res^{-1}day^{-1}$	%HHW in MSW
Berlin, Germany	1.06	4.3	1.7	62
Copenhagen, Denmark	0.8	30.3	2.23	36
Munich, Germany	1.02	40	1.62	63
Vienna, Austria	0.83	23.3	1.17	71
Budapest, Hungery	0.78*	34.7	1.22	64
Paris, France	0.9*	16.3	1.43	63
Stockholm, Sweden	0.62*	35.7	0.93	67
Zurich, Switzerland	0.76*	-	1.18	64

%OM: percent organic material
*Estimated values
Reference: Scharff & Vogel (1994)

Table 2.6 Domestic waste production in USA and Canada

Countries	USA		Canada	
Domestic waste kg $person^{-1}day^{-1}$	1.6		1.7	
Waste components	%	B.C.%	Ontario %	Quebec %
Paper	40	36	36	33
Glass	7	9	7.2	7.5
Yard + Food waste	25	22	31.5	32.2
Metals	8.5	11	6.5	6.8
Plastic	8	11	6.2	8.1
Others	11.5	11	12.6	12.4
Total waste	100	100	100	100

Reference: Environment Canada (1991), Laplante (1992)

Table 2.7 CH_4 production potential from food waste (FW)

CH_4 production potential	References
300.7 ml CH_4 g^{-1} of FW	Wang et al (1997)
200-500 ml CH_4 g^{-1} VS	Hansena et al (2004)

Table 2.8 Maximum recommended moisture contents for various composting materials

Type of waste	Moisture content (% of total weight)
Theoretical	100
Straw	75-85
Wood (sawdust, small chips)	75-90
Rice hulls	75-85
Municipal refuse	55-65
Manures	55-65
Digested or raw sludge	55-60
Wet waste (grass clippings, garbage, etc)	50-55

Reference: Golueke

Table 2.9 Optimum pH ranges for composting

pH ranges	References
7 – 9	Bidlingmaier et al (1985)
5.5 – 8.0	Zucconi et al (1986)
5.5 - 9.0 (preferred 6.5 to 8.0)	Pace et al (1995)

Table 2.10 Nitrogen and C/N ratio of waste

Material	N (% dw)	C/N ratio (mass basis)	References
Food waste	2.5	15	Maritinz & Otten (1999)
Wood chips	0.08	653	Maritinz & Otten (1999)
Wheat straw	0.46	92	Liang et al (1999)

Table 2.11 Nutrient content of various composting substrates

Material	Nitrogen As N (%dw)	Phosphorus as P_2O_5 (%dw)	Potash as K (%dw)	C/N ratio
Night soil	5.5-6.5			6-10
Urine	15-18			0.8
Blood meal	10-14	1-5		3.0
Animal tankage				4.1
Cow manure	1.7-2	1.0	2.0	18
Poultry manure	5-6.3	1.9	1.2	15
Sheepmanure	3.8			
Pig manure	3.8			
Horse manure	1.2-2.3	1.0	1.6	25
Raw sewage sludge	4-7			11
Digested sewage sludge	2-4	1.5	0.2	
Activated sludge	5			6
Grass clippings (green)	2.4-6			12-15
Grass clippings and weeds	2.0	1.1	2.0	
Mixed grasses	2.4			19
Nonlegume veg. Wastes	2.5-4			11-12
Bone meal	2.0	23		
Coffee grounds	2.1	0.3	0.3	
Cottonseed meal	6.6	2.0-3.0	1.0-2.0	
Eggshells	1.2	0.4	0.1	
Fish scraps	2.0-7.5	1.5-6.0		
Garbage	2.0-2.9	1.1-1.3	0.8-2.2	
Meat scraps	5-7			
Potato tops	1.5			25
Seaweed	1.7	0.8	4.9	
Salt marsh hay	1.1	0.3	0.8	
Straw, wheat	0.3-0.5			128-150
Straw, oats	1.1			48
Leaves, fresh	0.5-1.0	0.1-0.2	0.4-0.7	41
Sawdust	0.1			200-500
Food wastes	3.2			15.6
Mixed paper	0.19			227
Yard wastes	1.95			22.8
Wood ashes		0.1-2.0	4.0-10	

Reference: Adapted from Glueke, Poincelot, and Kayhanian & Tchobanoglous.

CONNECTING STATEMENT TO CHAPTER THREE

The treatment and reduction of urban food waste (UFW) production reduces pressure on municipal solid waste (MSW) landfill systems both in developed and developing economies. Therefore, estimated growth of UFW production for the upcoming decades provides an opportunity to make future urban waste management strategy for its treatment. Chapter three examines the predicted growth of UFW with possible alternate solutions to reduce pressure on urban waste management systems.

This chapter is drawn from a manuscript prepared for publication by the author of the thesis and co-authored by his supervisor, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University and Dr. Jose Martinez, Director of Research, CEMAGREF, France. The format has been changed to be consistent within this thesis.

CHAPTER THREE
PREDICTED GROWTH OF FOOD WASTE PRODUCTION FROM URBAN AREAS AROUND THE WORLD

ABSTRACT

The landfilling of food waste (FW) along with municipal solid wastes (MSW) leads to several environmental problems such as the formation of leachate contaminating groundwater and the emission of greenhouse gases. To develop other treatments besides landfilling for FW, their production rate must be predicted. This chapter presents evidence that gross domestic product (GDP, US$/capita) is the key factor governing growth the percentage of population living in urban as opposed to rural areas, and determining the production of MSW and urban FW (UFW). For several world countries, this chapter then predicts urban population (UP) and UFW production as a function of population growth and GDP growth. Furthermore, this chapter examines the effect on UFW production of introducing policies to improve the economic situation in rural areas, and stopping the movement of people towards cities.

On a global scale, MSW and UFW production are expected to increase by 94% and 76% from 1995 to 2025. Because of its expected economic development, Asia is expected to experience the largest increase in UFW, from 220 million tons to 418 million tons from 1995 to 2025. From 1995 to 2025, UFW disposed in landfills will potentiality increase world CH_4 emissions from 27 million tons to 48 million tons and the landfill share of global anthropogenic emissions from 8% to 10%. Encouraging people to stay in rural areas where they can easily use their FW as soil amendment, can lead to 30% decrease in UFW production by the year 2025 and the drop in the landfill share of the global anthropogenic emissions from 10% to 7%.

3.1 Introduction

Among all fractions found in municipal solid wastes (MSW), food waste (FW) is the most active biologically. Uncollected, UFW attracts disease vectors such as microbes, insects and rats, and decomposes to produce leachate contaminating runoff and greenhouse gas emissions (GGE). Collected and conventionally eliminated through landfills, UFW uses large surfaces of valuable land, especially in developing countries, produces large volumes of contaminated leachate risking groundwater pollution and emits important quantities of greenhouse gases further contributing to earth warming trends.

In consideration of the steadily increasing world population and of countries like China and India, with large populations experiencing significant economic growth, the production of FW is likely to increase and impose even more global environmental pressure. Since the price for agricultural produce at the farm has not increased for over 30 years because of world trading policies, any improvement in the economic welfare of a country leads to a greater gap between rural and urban employment opportunities, thus resulting in more people finding their way into cities. A higher percentage of people living in cities will put more stress on already overburdened MSW management systems by requiring more transportation facilities to handle more waste transported over greater distances as city borders expand. More elaborate treatment systems will be needed especially if the treatment is conducted on the outskirts of the city. The management of the FW fraction of MSW is less of an issue in rural communities, because of it can easily be recycled as a soil amendment.

The aim of this chapter is to provide some foresight into the mass of urban FW (UFW) to be managed by cities around the world by the year 2025. The prediction of such quantities, along with the management method selected, provides a tool to evaluate the impact of UFW on the required size of treatment systems, such as the extent of landfill operations and the resulting environmental impacts such as the landfill land usage, groundwater contamination risks and greenhouse gas emissions. The first objective of this chapter is therefore to test the hypotheses that, as a country's per capita Gross Domestic Production (GDP, $US) increases, so does the percentage of people living in urban as opposed to rural areas, and so does the per capita MSW and UFW production. Other factors such as availability of food, food habit, social and political scenarios may have impact on movement of people from rural to urban centers and UFW production. However, in this study, GDP has been considered one of the major factors affecting movement of people from rural to urban centers and UFW production. Having demonstrated that such hypotheses hold, equations will be developed to predict the amount of UFW produced in countries around the world by the year 2025. Finally, two scenarios will be examined to evaluate their impact on reducing UFW production: the first will assume no further movement of the world population towards cities, with rural communities disposing of 75% of their FW as soil amendments, and; the second will presume that 75% of all UFW can be composted or anaerobically digested on site, within cities, rather than sent to landfills, and that such treatments will reduce GGE by 25%, as compared to landfilling.

3.2 Literature review

Urban food waste (UFW) constitutes 50% to 80% of the MSW stream in the urban areas of low and middle-income countries, and 25% to 30% in that of high-income countries (Achankeng 2003).

Already required to manage an enormous quantity of MSW, many world cities are faced with an accumulation problem because of the physical and economic pressures placed on disposal systems (Chakrabarti & Sarkhel 2003). The improper handling of MSW is already posing a serious threat to human health in many large cities of the world (Lu 1995, Ahmed & Jamwal 2000, Hong et al 1996). With better economic conditions implying the movement of population towards urban centers, this problem is likely to get worse for countries of low to medium income, where presently over 65% of the population dwells in rural areas, as compared to 8% for high income countries such as Canada (UNCHS 2005).

In low to medium income countries, city authorities do not have the resources to collect all the MSW generated, and for that collected, only a fraction receives proper disposal. In India, Pakistan (Karachi) and Egypt (Cairo), only 50%, 33% and 50% of the generated MSW is collected, respectively (Sinha & Enayetullah 1995, Medina 2002), and 90% of the collected MSW is disposed in open dumps (Medina 2002). In Africa, up to 80% of the waste is either not collected, or collected but illegally dumped (Achankeng 2003).

Uncollected MSW is a major health problem for a city as it accumulates in streets, clogs sewers when it rains leading to floods, and runs into rivers or lakes where it further contaminates the ecosystem (Medina 2002, Chakrabarti & Sarkhel 2003). A 1997 survey indicated that over 90% of China's and India's population felt that their health was adversely affected by environmental problems resulting from improper MSW management (China Waste Management 2004, World Bank 1999). Such poor MSW management led to the outbreak of plague in Surat, India, in September 1994 (Venkateshwaram 1994). In 1994, WHO (1995) reported 617 000 cases of cholera resulting in 4400 deaths all over Africa (Angola, the Democratic Republic of the Congo, Malawi, Mozambique and Tanzania). In Malawi, Mozambique and Zimbabwe, Holloway (1995) reported 600 deaths resulting from 171 000 cases of dysentery.

When landfilled, UFW leads to GGE and the enrichment of atmospheric CH_4 (Cicerone & Oremland 1988, Dlugokencky et al 1998, Shipham et al 1998, Rasmussen & Khalil 1984), a major greenhouse gas (Burton & Turner 2003) trapping 21 times more heat per unit mass than CO_2 (IPCC 2001).

In landfill sites, FW release gases with 60% to 65% CH_4 and 35% to 40% CO_2 (Legg 1990, Borjesson & Svenssen 1997, Hong et al 1996, Solid Waste Landfill Guidance 1999). According to Wang et al. (1997), FW generates 300L of CH_4 (dry kg)$^{-1}$. In a laboratory experiment, Hansen et al (2004) found that FW produces from 200 to 500L of CH_4 kg^{-1} of volatile solids (VS).

Thus, landfills are responsible for approximately 8% of the anthropogenic world CH_4 emissions (USEPA 1994), with higher percentages of 37% and 30% being observed in high income countries such as the US and those of Europe, respectively (USEPA 2003, EEA 2001).

Once landfilled, FW is known to decompose and produce liquid which leaches organic and inorganic contaminants (Bou-Zeid & El-Fadel 2004, Bilitewsi et al 1994) considered to be a major sources of groundwater contamination (Gonullu 1994, Zacharof & Butler 2004). Therefore, contamination of water resources from landfill leachate can be minimized by the source separation of FW, which represents the major organic fraction of the MSW stream.

3.3 Testing the hypotheses

The study was designed to produce equations predicting the future production of UFW for countries around the world. These equations are based on the hypotheses that GDP is the main force behind the movement of population from rural to urban centers and the increase in both MSW and FW production. If these hypotheses are true, then UFW production can be predicted as a function of future world population, and as a function of the effect of GDP on mass of MSW and FW produced.

To test these hypotheses, regression equations will be formulated between GDP and percentage urban population (UP), and between GDP and MSW as well as FW production (Excel, Microsoft 2003). The value of such regression coefficient will be a measure of the validity of the equations produced.

For different countries around the world, Tables 3.1a, 3.1b, 3.1c and 3.1d present values of GDP, percentage urban population (%UP), totals population (TP) and population growth. Based on the data presented in Tables 3.1a-3.1d, growth in GDP was correlated to %UP (Figure 3.1).

The following equations are obtained from the correlation of GDP and %UP for different countries in Africa, Asia, Europe and the Americas, respectively (Figures 3.1a, 3.1b, 3.1c and 3.1d):

$$(\%UP)_{afc} = [15.547 * \text{Ln}\,(GDP)_{afc}] - 56.674 \qquad (R^2 = 0.90) \qquad (3.1a)$$

$$(\%UP)_{ac} = [15.06 * \text{Ln}\,(GDP)_{ac}] - 51.539 \qquad (R^2 = 0.90) \qquad (3.1b)$$

$$(\%UP)_{ec} = [10.087 * \text{Ln}\,(GDP)_{ec}] - 15.242 \qquad (R^2 = 0.86) \qquad (3.1c)$$

$$(\%UP)_{amc} = [12.88 * \text{Ln}\,(GDP)_{amc}] - 38.769 \qquad (R^2 = 0.85) \qquad (3.1d)$$

where:

(%UP) = percentage of urban population for a given continent in 1995;

(GDP) = GDP for a given continent in 1995;

Subscripts afc, ac, ec and amc = pertaining to Africa, Asia, Europe and the Americas.

Relatively high correlation coefficients of 0.90 were obtained for Africa and Asia, while slightly lower but still valid coefficients (R^2 = 0.85) were obtained for Europe and the Americas. This difference is most probably due to the fact that in Europe and the Americas, agricultural production is subsidized, leading to the maintenance of rural populations and a slight variation in the relationship between GDP and %UP.

The data gathered in Table 3.2 was used to correlate GDP to MSW and FW production (Figure 3.2):

$(MSWPR)_{CRY} = [8 * 10^{-5} (GDP)_{CRY}] + 0.5114$ ($R^2 = 0.94$) (3.2a)

$(FWPR)_{CRY} = [10^{-5} * (GDP)_{CRY}] + 0.3157$ ($R^2 = 0.81$) (3.2b)

where:

$(MSWPR)_{CRY}$ = MSW Production Rate, kg capita^{-1}day^{-1};

$(GDP)_{CRY}$ = GDP, US$;

$(FWPR)_{CRY}$ = FW production rate, kg capita^{-1}day^{-1};

Subscripts CRY = C for country, R for continent and Y for year.

Although the production of MSW is well correlated with GDP ($R^2 = 0.94$), the production rate of FW demonstrates a slightly lower but still valid correlation coefficient of 0.81 with GDP. This lower correlation value between FW production and GDP is likely due to variations in food habits, availability of fresh food supply and amount of food processing generally leading to more FW. Production rates and composition of FW vary with country, availability of resources and season (Abu Qdais et al 1997, World Bank 1999). Medina (2002) also found a positive correlation between income and the amount of MSW produced. For example, China Waste Management (2004) reported an economic growth during the last two decades of almost 10% along with an annual increase in MSW generation of 8% to10% and UP increased from 30% to 35% in the period of 1997 to 2003.

Accordingly, the likelihood that growth in GDP can predict growth in %UP, MSW and UFW production is relatively high for Africa and Asia, where most of the world population is found, and slightly less accurate for Europe and the Americas. Furthermore, the largest changes in GDP are expected to occur in Asia, where higher correlation coefficients were obtained. Accordingly, the overall prediction for the world can be relatively accurate.

3.4 Predicted growth of MSW, UFW and CH_4

3.4.1 Expected GDP and UP growth

Growth in GDP is the first element to compute, as it is required along with world population growth to predict changes in %UP and growth in production of MSW and UFW. The GDP of individual countries around the world was estimated by considering the average growth rate as presented in Table 3.3. Using the GDP of a country for 2000, average annual GDP growth rate was used to predict GDP for the years 2005, 2010, 2015, 2020 and 2025, as follows:

$$(GDP)_{SY} = \{(GDP)_{GY}/100^{(SY-GY)}\} * (100 + y)^{(SY-GY)} \quad (3.3)$$

where:

$(GDP)_{SY}$ = GDP for a future year;

$(GDP)_{GY}$ = GDP for a year in which GDP is known;

y = Average annual growth rate of GDP for specific country, %;

Subscripts SY and GY = Specific and given year in which GDP is to be estimated.

With the growth in GDP for a representative number of countries around the world, growth in %UP was computed for 2005 and 2025 as a function of GDP (Table 3.4). Accordingly, the total urban population (TUP) was predicted for 2025, based on the predicted population and %UP growth of the country.

The calculations predict, for example, that China which has experienced a GDP growth from 2005 to 2025, from 1018 US$ to 2455 US$ with a UP increasing from 53% to 66%. Similarly, the US is expected to experience a GDP growth from 34073 US$ to 44116 US$, with an increase in UP from 96% to 99%, for the same period.

3.4.2 Predicting MSW, UFW and CH_4 production

Using equations 3.1, 3.2 and 3.3, and the data in Tables 3.1a-3.1d, 3.2 and 3.3, equations were formulated to predict the increase in MSW and UFW production, based on GDP growth:

$$(MSWP)_{CRY} = 3.65 * 10^{-9} * (UP)_{CRY} * (MSWPR)_{CRY} * (TP)_{CRY} \quad (3.4a)$$

$$(UFWP)_{CRY} = 3.65 * 10^{-9} * (UP)_{CRY} * (FWPR)_{CRY} * (TP)_{CRY} \quad (3.4b)$$

$$(\%UFW)_{CRY} = [\{(UFWP)_{CRY}\}/ \{(MSWP)_{CRY}] * 100 \quad (3.4c)$$

where:

$(MSWP)_{CRY}$ = MSW production, million ton year^{-1};

$(UP)_{CRY}$ = UP, %;

$(TP)_{CRY}$ = total population;

$(UFWP)_{CRY}$ = UFW production, million ton year^{-1};

$(\%UFW)_{CRY}$ = UFW as % of MSW;

Subscripts CRY = C refers to the country, R to the continent and Y to the year.

Also, a relation is formulated to estimate CH_4 emission from landfilled UFW:

$$(CH_4P)_{CRY} = \alpha * (\%DW/100) * (UFWP)_{CRY} \qquad (3.5)$$

where:

$(CH_4P)_{CRY}$ = CH_4 production, million ton year^{-1};

α = CH_4 production potential as 0.204 kg CH_4 kg^{-1} dry weight of FW (Wang et al 1997);

%DW = Dry weight of FW, 30% (Peavy et al 1985);

Subscripts CRY = C refers to the country, R to the continent and Y to the year.

The predicted growth of UFW and percentage of UFW in MSW from 1995 to 2025, as computed using equations 3.4 and 3.5 are illustrated in Figures 3.3 and 3.4, for various countries around the world. Also, the data for selected countries are presented in Table 3.5 for 2010 and 2025.

Asia is and will continue to be a major contributor in UFWP because of its rapid urban growth coupled with its increasing economic activity. Asia will increase its UFWP from 220 million tons to 418 million tons from 1995 to 2025 (Figure 3.3). China and India will generate remarkable amount of UFW (Table 3.5), representing 25% of total global UFW production in 2010 and about 26% in 2025, for 33% of the world urban population. The Americas will follow Asia increasing their UFWP from 99 million tons to 168 million tons, in 2025. The US, Brazil and Mexico are major producers of UFW, followed by Canada, Argentina, Peru and Chili. The Brazil and US will generate 91 million tons and 115 million tons of UFW in 2010 and 2025, respectively, representing 15% of total global UFWP for 10% of the world urban population.

In Africa, the production of UFW is expected to increase from 34 million tons to 81 million tons from 1995 to 2025, for a 4.6% average annual growth rate in 30 years (Figure 3.3). Egypt and South Africa are expected to produce 11 million tons and 15 million tons in 2010 and 2025, respectively, followed by Morocco, Sudan and Nigeria. In Europe, France, Italy, Germany, England and Russia are expected to produce 66 million tons and 76 million tons in 2010 and 2025, respectively, representing 10% of total global UFW production for 6% of the world population.

From 1995 to 2025, the percentage of UFW in MSW also varies among countries within continents, depending on economic growth and income level (Figure 3.4). Higher economic growth and income level produce lower % of UFW in MSW due to consumption of more processed foods (Medina 2002). In Africa, the percentage of UFW in MSW is expected to drop from 53% to 50%; among its countries, this percentage will vary from 23% to 59% in 2025. Africa is followed by Asia, where the percentage of UFW in MSW will drop from 46% to 42%; among its countries, this percentage will vary from 17% to 58% in 2025. In the Americas, the percentage UFW in MSW is expected to drop from 43% to 37% in 2025 and; among its countries, it is expected to vary from 17% to 59% in 2025. In Europe, this percentage will drop from 36% to 30% in 2025, and; among its countries, it is expected to vary from 16% to 57% in 2025.

3.5 Predicted growth of CH_4 from UFW

The abundance of atmospheric CH_4 continues to rise (Cicerone & Oremland 1988, Dlugokencky et al 1998, Shipham et al 1998) as a function of world population (Rasmussen & Khalil 1984). According to Safley et al (1992), the annual per capita CH_4 production is about 60 kg and results from waste handling, biomass burning, agriculture, industrial processes, biofuel and fossil fuel.

The predicted trend of CH_4 production (equation 3.5) is illustrated in Figures 3.5 and 3.6. Also, that produced by selected countries is presented in Table 3.5, for 2010 and 2025. Asia will show the largest increase in CH_4 generated from UFW, going from 13 to 26 million tons from 1995 to 2025 followed by the Americas going from 6 million tons to 10 million tons. China and India alone are expected to produce 2.3% of total global anthropogenic CH_4 production in 2010 and about 3% in 2025. In the Americas, the US, Brazil and Mexico are major contributors to global CH_4 emission followed by Canada, Argentina, Peru and Chili. The US and Brazil are expected to produce 5.5 and 7 million tons of CH_4 in 2010 and 2025, respectively, representing 1.5% of total global anthropogenic CH_4 production. The African CH_4 production is expected to increase from 2 million tons to 5 million tons from 1995 to 2025, for a 5% average annual growth over 30 years. Egypt and South Africa are expected to produce 0.67 million tons and 3.8 million tons in 2010 and 2025, respectively, followed by Morocco, Sudan and Nigeria. In Europe, France, Italy, Germany, England and Russia are expected to produce 4 million tons and 4.7 million tons in 2010 and 2025, respectively, or 1% of the world global anthropogenic CH_4 production (Table 3.6). The total global CH_4 production from UFW is expected to increase from 27 million tons to 48 million tons from 1995 to 2025, representing an increase from 8% to 10% of total anthropogenic CH_4 production.

3.6 Scenarios to minimize UFW effects

Whereas sections 3.4 and 3.5 illustrate the present trend using a "Do nothing scenario", the following section will examine some alternative and their impact on UFW production. The first scenario will examine the effect of no population movement to urban centers and the recycling of 75% of rural FW as soil amendments or for biogas production. The second scenario will examine the effect of using other disposal systems besides landfills.

3.6.1 Scenario one: stable %UP

Various factors compel the world population to move to cities and there are some major environmental benefits in stopping this movement. The major issue is the economy of rural areas around the world. The price paid for fresh agricultural produce establishes the economic wealth of rural communities in countries, regardless of the country's income level. During the last 30 years, farm gate prices have not increased whereas other goods and services have experienced a ten fold increase. Faced with long hours of hard work and limited income, children of farming families generally leave rural areas for better opportunities in the city. Because of such poor economic conditions, farms are handed down from one generation to the next, with relatively no outsiders bringing new production ideas. These factors have lead to the deterioration of the economic conditions in rural areas, with little being done to change its condition, even in countries like the US, Canada and many countries of Europe.

This situation has resulted and will bring about even higher percentages of populations living in urban centers. In 1995, 3.12 billion or 55% of total world population was living in cities and this will shift in 2025 to 5.2 billion or 65% of total world population. Currently, 3.8 billion people live in urban centers representing 57% of total world population. However, rural population is estimated to remain at 2.8 billion from 2005 to 2025. China will experience the greatest shift towards UP, if it maintains its economic growth, going from 44% to 66% from 1995 to 2025.

Reducing the world population movement from rural to urban areas can be achieved through formulating world trade policies for agricultural produce insuring a better price at the farm gate in exchange for more sustainable practices. Perhaps world quota systems would then be needed to govern production in terms of consumption. The impact of higher food prices on the standard of living of lower to middle income countries would have to be curtailed by internal policies. Nevertheless, higher prices for farm produce would induce higher GDP for lower to middle countries depending presently on international trade for the sale of commodities such as tea, coffee, sugar and fresh fruits and vegetables.

As compared to the "Do nothing" scenario, the result of curtailing UP growth is illustrated in Figure 3.7. Better rural conditions would result in 47% of the world population living in cities, in 2025, compared to 57% if nothing is done. This trend would keep 1.47 billion people in rural areas from 1995 to 2025, reducing UFW by 239 million tons, which if recycled as soil amendment, would reduce CH_4 emission by 15 million tons or 3% of total global anthropogenic CH_4 emissions. This would also save from landfill operations, about 40 million ha yr^{-1} of land and make it available for other more productive purposes.

3.6.2 Scenario two: composting or digesting UFW on site, rather than landfilling

If beside better rural economic policies, cities were to treat their UFW through composting or anaerobic digestion, even more CH_4 emissions can be curtailed while improving crop yields (Chakrabarti & Sarkhel 2003).

Besides a 75% reduction in GGE, the on site recycling of UFW would reduce MSW transportation load by 40%. In continents such as Africa and Asia, 50% less MSW would require transportation and landfilling. This will save the cost of waste collection, transportation and save the land required for landfilling, as well as reduce the environmental ramifications.

3.7 Conclusion

This study demonstrates that GDP is an influential factor in the growth of UP and UFW. The growth of urbanization and economic activities of large cities around the world contribute to the growing trend of UFW generation especially in developing economy. Therefore, UFW management should be considered seriously and that current planning should reflect a will to deal with this looming problem. If this "do nothing scenario" continues over upcoming decades, MSW management will impose tremendous pressure on cities around the world, both financially and environmentally. Instead, two solutions are proposed:

(1) Scenario one: making rural economies more attractive and creating favorable living environment in the rural areas so that there will be reduced movement of people from rural to urban areas, and;
(2) Scenario two: on site aerobic or anaerobic digestion within cities of UFW rather than sending UFW to landfill.

These two scenarios can reduce the pressure pertaining to MSW management in world's cities. However, both the scenarios demand social and political commitment.

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Table 3.1a GDP, %UP and total population (TP) growth of various African countries

Country	GDP capita^{-1} (US$) 1995	UP (%) 1995	TP (10^6) 1995	Average annual growth of total population in % (1995-2025)
Comoros	168	30.5	0.61	3.98
Ethiopia	96	15.4	56.40	4.72
Eritrea	181	17.1	3.17	3.50
Kenya	331	28.6	27.15	2.83
Madagascar	229	26	14.87	-0.94
Malawi	143	14	9.67	3.69
Mozambique	141	34	17.26	3.51
Somalia	130	26	9.5	4.98
Tanzania	170	24	30.03	3.60
Cameroon	652	45	13.19	3.87
Central. Afr. Rep	333	39	3.27	2.78
Chad	214	22	6.33	3.32
Equatorial Guinea	409	42	0.40	3.32
Algeria	1509	56	28.11	2.28
Libya	6366	85	5.41	4.61
Morocco	1229	52	26.52	1.68
Sudan	296	31	26.71	2.13
Tunisia	2014	62	9.0	1.68
Egypt	976	45	62.1	1.81
Botswana	2854	60	1.45	2.59
South Africa	3692	75	41.5	2.42
Benin	367	38	5.41	4.23
Burkina Faso	223	16	10.5	4.13
Cape Verde	1026	54	0.4	2.53
Cote d'ivoire	696	43.4	13.7	2.61
Gambia	360	29	1.11	2.62
Ghana	369	35.9	17.34	3.65
Mali	230	26.8	10.8	4.26
Niger	185	18.2	9.15	4.82
Senegal	537	44	8.31	3.44
Sierra Leone	213	33	4.2	3.18
Togo	273	31	4.1	3.82

Reference: IEA (2002), UNCHS (2005)

Table 3.1b GDP, %UP and total population (TP) growth of various Asian countries

Country	GDP $capita^{-1}$ (US$) 1995	UP (%) 1995	TP (10^6) 1995	Average annual growth of total population in % (1995-2025)
China	575	30.2	1220.3	0.71
Hong Kong	22935	95	6.12	0.21
Macau	16938	98.8	0.43	0.98
Mongolia	400	60.8	2.5	2.15
Afghanistan	92	19.9	19.7	4.34
Bangladesh	307	18.3	118.23	1.74
India	393	26.8	929.0	1.44
Kazakhstan	1039	59.6	16.82	0.64
Kyrgyzstan	327	38.8	4.46	1.11
Pakistan	473	34.3	136.26	3.25
Tajikistan	113	32.2	5.83	2.24
Uzbekistan	448	41.1	22.76	2.01
Cambodia	253	20.4	10.03	2.32
Singapore	23876	100	3.33	0.89
Bahrain	9914	90.3	0.56	1.83
Israel	16778	90.7	5.52	1.48
Jordan	1584	71.4	5.37	4.05
Kuwait	15621	97	1.7	2.39
Qatar	15650	91.4	0.55	1.42
Saudi Arabia	6738	82.8	18.26	4.40

Reference: IEA (2002), UNCHS (2005)

Table 3.1c GDP, %UP and total population (TP) growth of various European countries

Country	GDP $capita^{-1}$ (US$) 1995	UP (%) 1995	TP (10^6) 1995	Average annual growth of total population in % (1995-2025)
Republic of Moldova	332	51.6	4.4	0.32
Poland	3299	63.7	38.6	0.12
Romania	1564	55.9	22.7	-0.24
Russian Federation	2281	75.9	148.5	-0.38
Denmark	34466	85.2	5.2	0.06
Iceland	25886	91.5	0.27	0.83
Sweden	28133	83.1	8.79	0.27
United Kingdom	19675	89.2	58.08	0.08
Albania	752	37.2	3.4	0.90
Spain	14685	76.5	39.63	-0.18
Republic of Macedonia	2275	59.9	2.16	0.60
Yugoslavia	1166	56.6	10.25	0.14
Belgium	27304	97	10.13	0.05
Germany	30104	86.5	81.6	-0.03
Luxembourg	44106	89.1	0.40	0.48
Netherlands	25769	89	15.5	0.14
France	25769	89	15.5	9.67

Reference: IEA (2002), UNCHS (2005)

Table 3.1d GDP, %UP and total population (TP) growth of various American countries

Country	GDP $capita^{-1}$ (US$) 1995	UP (%) 1995	TP (10^6) 1995	Average annual growth of total population in % (1995-2025)
Bermuda	33333	100	0.06	0.58
Canada	20170	76.7	29.40	0.79
United States America	28149	76.2	267.11	0.82
Bahamas	10962	86.5	0.28	1.34
Cayman Island	30120	100	0.03	2.80
Dominica	2739	69.3	0.71	0.52
Dominican Republic	1552	61.9	7.82	1.24
Haiti	325	31.8	7.12	2.52
Trinidad and Tobago	4230	71.7	1.3	1.05
Honduras	702	43.8	5.65	2.95
Mexico	3146	73.4	91.14	1.43
Brazil	4386	78.4	159.01	1.21
Ecuador	1574	58.9	11.5	1.84
Guyana	840	35.4	0.83	1.14
Suriname	1263	49.2	0.43	1.39

Reference: IEA (2002), UNCHS (2005)

Table 3.2 GDP, %UP, MSW and FW of various countries around the world

Country	GDP capita^{-1} (US$) 1995	UP (%) 1995	WSW (kg capita^{-1}day^{-1}) 1995	FW (kg capita^{-1}day^{-1}) 1995
Nepal	207	10.3	0.5	0.32
Bangladesh	307	18.3	0.49	0.32
Gambia, The	360	29	0.3	0.19
Benin	367	38.4	0.5	0.32
Ghana	369	35.9	0.4	0.26
India	393	26.8	0.46	0.35
Senegal	537	43.7	0.5	0.32
Bolivia	898	60.5	0.5	0.32
Egypt	976	44.6	0.5	0.32
Philippines	1084	54	0.52	0.25
Morocco	1229	51.9	0.6	0.39
Paraguay	1867	52.4	0.64	0.39
Thailand	2829	20	1.1	0.43
Poland	3299	63.7	0.95	0.40
Venezuela	3535	85.8	0.94	0.38
Hungary	4375	64.6	1.1	0.46
Korea, South	10863	81.3	1.59	0.44
United Kingdom	19675	89.2	1.95	0.55
Australia	19899	84.7	1.95	0.54
Canada	20170	76.7	1.85	0.51
United States	28149	76.2	2.78	0.75

Reference: IEA (2002), World Resources (1998-99), OECD (1995), Diaz et al (1986), Beed & Bloom (1995), Ward (1993), USEPA (1999), UNCHS (2005), Diaz et al (1993)

Table 3.3 Average annual growth rate of GDP in %

Regions/countries	year	GDP $capita^{-1}$
North America (except Mexico but including Latin America)	2000-2030	1.3
Western Europe	2000-2030	1.8
Japan, Pacific region	2000-2030	1.6
Eastern Europe	2000-2030	3.0
Former USSR	2000-2030	3.4
Latin America	2000-2030	2.1
South- East Asia	2000-2030	3.0
China	2000-2030	4.5
India sub continent	2000-2030	3.3
North Africa and Middle East	2000-2030	1.4
Sub- Sahara Africa	2000-2030	1.7
World	2000-2030	2.0

Reference: CEPII (2002)

Table 3.4 Computed GDP, TUP and %UP growth for several world countries

Continent/country	GDP (US$) 2005	GDP (US$) 2025	TUP (10^6) 2005	UP (%) 2005	TUP (10^6) 2025	UP (%) 2025
Africa						
Egypt	1268	1675	40.4	54%	56.3	59%
Morocco	1443	1905	17.7	56%	24.3	61%
Sudan	398	525	12.1	36%	17.8	41%
South Africa	4256	5962	37.6	73%	56.2	78%
Nigeria	1003	1405	74.9	51%	133.5	56%
Asia						
China	1018	2455	697.3	53%	977.3	66%
India	561	1074	473.9	44%	712.5	54%
Nepal	275	527	9.1	33%	17.4	43%
Vietnam	436	835	34.7	40%	54.8	50%
Indonesia	1164	2229	124.3	55%	177.7	65%
Europe						
France	32680	46691	53.4	90%	56.3	93%
Italy	22952	32792	48.8	86%	46.4	90%
Germany	35716	51029	75.0	91%	76	94%
England	24391	34849	50.7	87%	53.7	90%
Russia	2837	5536	93.3	65%	94.2	72%
Americas						
Canada	24607	31860	29.1	91%	34.5	95%
United States	34073	44116	275.3	96%	329.1	99%
Mexico	4186	6344	72.9	69%	96.3	74%
Argentina	8773	13294	30.7	78%	39.4	84%
Brazil	5079	7697	127.6	71%	165.7	76%
Chili	6355	9630	12	74%	15.5	79%
Peru	2598	3938	17.4	63%	24.1	68%

Table 3.5 Computed UFW production for several world countries

Continent/ Country	UFW (10^6 x ton) 2010	*PC MSW 2010	UFW (10^6 x ton) 2025	PC MSW 2025
Africa				
Egypt	5.32	52	6.8	50
Morocco	2.32	51	3.0	49
Sudan	1.6	57	2.0	56
South Africa	5.53	40	7.7	37
Nigeria	0.45	58	0.8	58
Asia				
China	90.93	52	120.4	47
India	62.2	55	84.2	53
Nepal	1.3	57	2	56
Vietnam	4.54	56	6.5	54
Indonesia	16.33	52	21.8	48
Europe				
France	13.3	20	16.0	18
Italy	10.1	22	10.9	21
Germany	19.4	19	23	18
England	11.0	22	13.0	20
Russia	12	45	12.8	39
Americas				
Canada	6.4	22	8	21
United States	71.5	20	90.9	19
Mexico	10.4	41	13.3	37
Argentina	5.0	32	6.5	28
Brazil	18.7	39	23.7	35
Chili	1.8	36	2.3	32
Peru	2.4	46	3.1	43

*PCMSW = Percentage of country total municipal solid waste production

Table 3.6 Computed CH_4 production for several world countries

Continent/ Country	CH_4 (10^6 x ton) 2010	CH_4 (10^6 x ton) 2025	Average annual growth in % (2010 – 2025)
Africa			
Egypt	0.33	0.42	1.82
Morocco	0.14	0.18	1.90
Sudan	0.1	0.13	2.00
South Africa	0.34	0.47	0.90
Nigeria	0.03	0.05	0.13
Asia			
China	5.6	7.4	2.15
India	3.8	5.15	2.37
Nepal	0.08	0.12	3.33
Vietnam	0.28	0.40	2.85
Indonesia	1.00	1.33	2.2
Europe			
France	0.81	0.98	1.4
Italy	0.61	0.67	0.65
Germany	1.2	1.4	1.1
England	0.67	0.80	1.3
Russia	0.73	0.78	0.45
Americas			
Canada	0.40	0.49	1.5
United States	4.38	5.56	1.8
Mexico	0.64	0.81	1.7
Argentina	0.30	0.40	2.2
Brazil	1.14	1.45	1.80
Chili	0.11	0.15	2.42
Peru	0.15	0.20	2.22

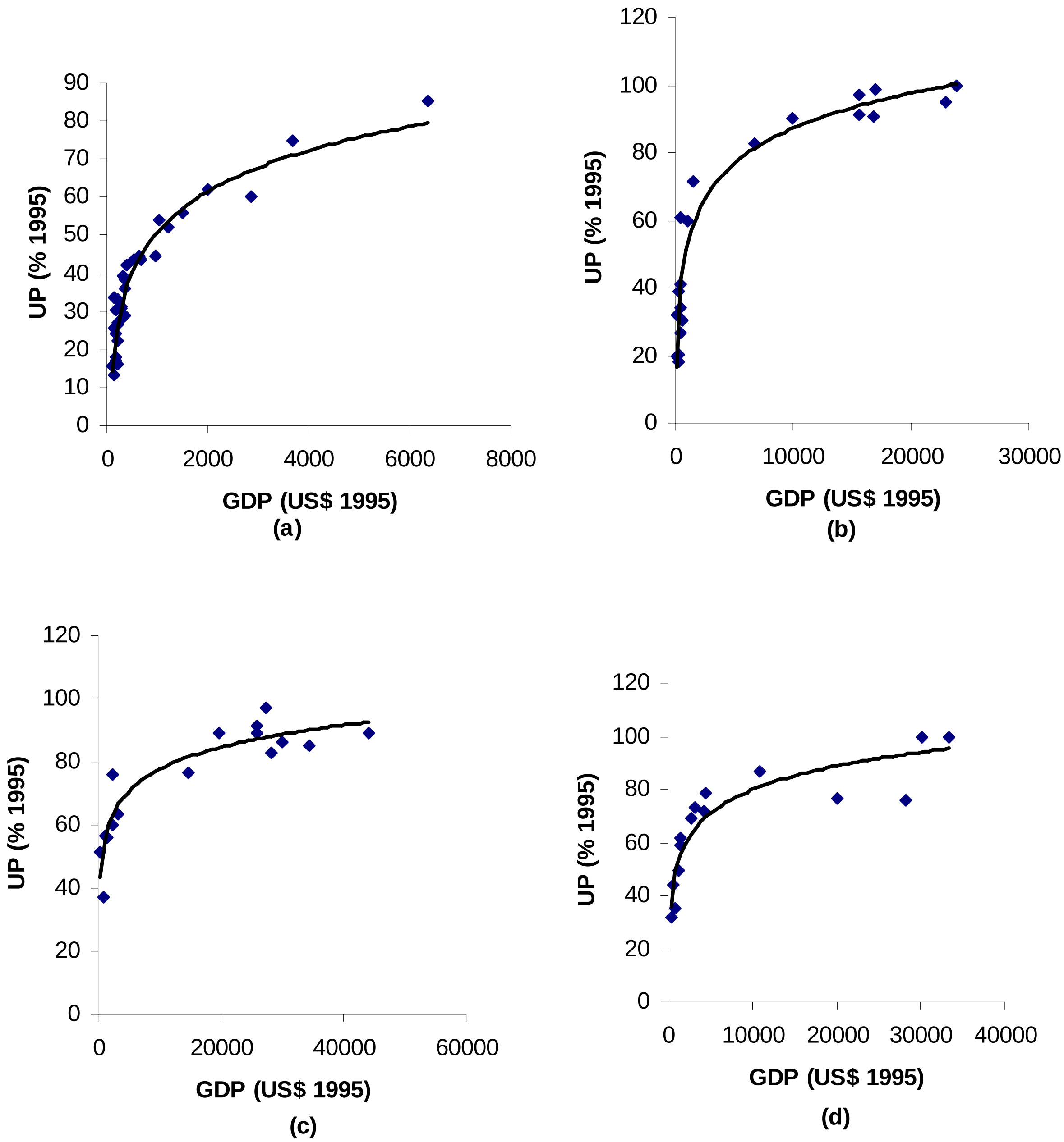

Figure 3.1 Illustrating UP as a function of GDP for each continent (a) Africa (b) Asia (c) Europe (d) America

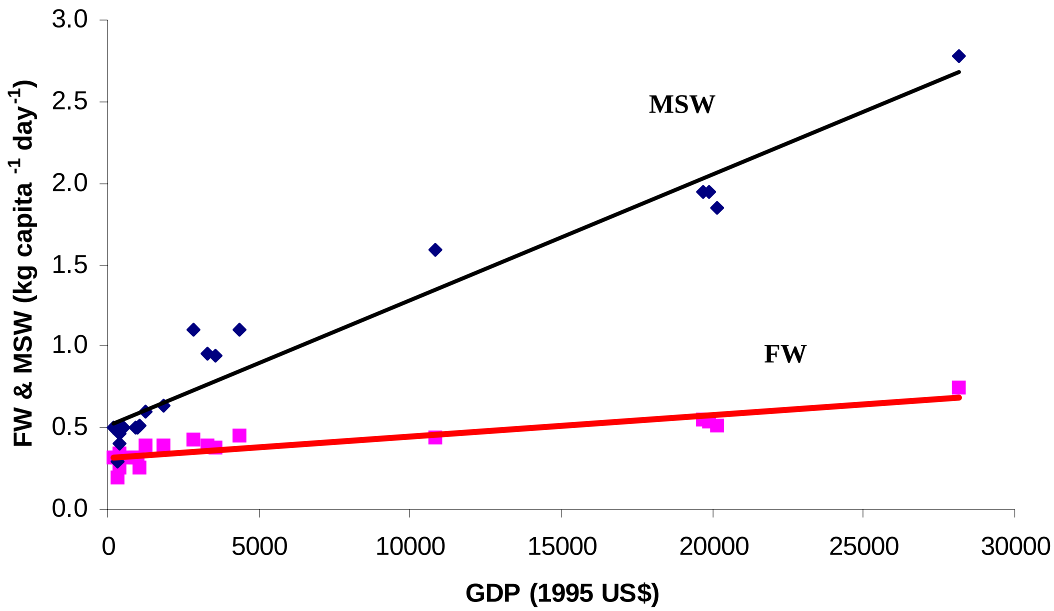

Figure 3.2 FW & MSW production as a function of GDP

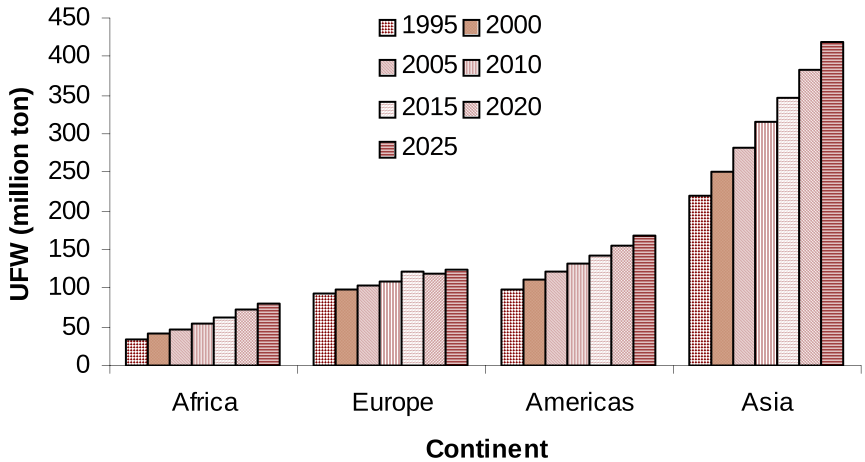

Figure 3.3 Continental UFW production

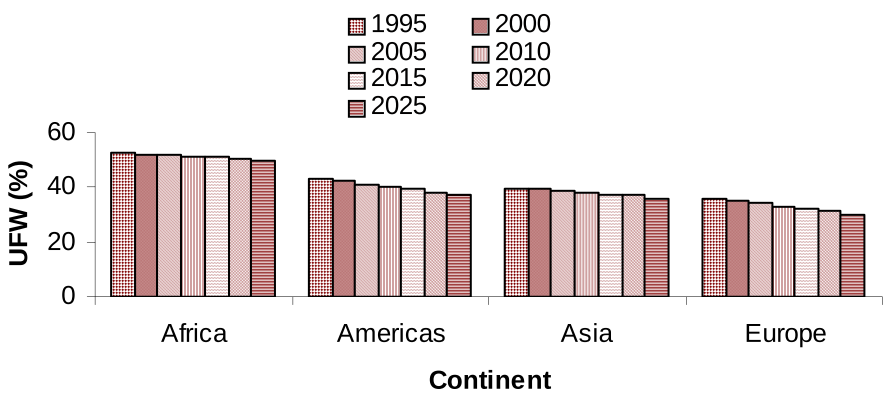

Figure 3.4 Fraction of UFW in MSW for different continents

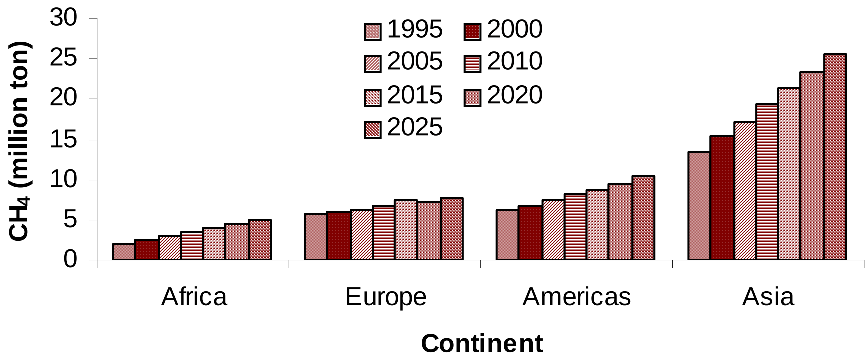

Figure 3.5 Continental CH_4 emission from UFW if untreated

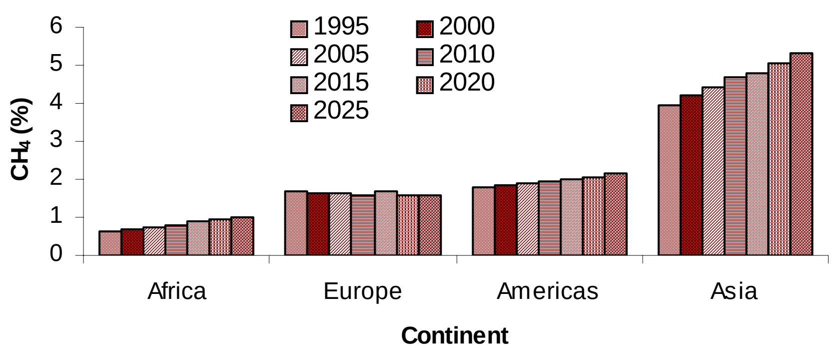

Figure 3.6 Percentage of total global CH_4 production from UFW

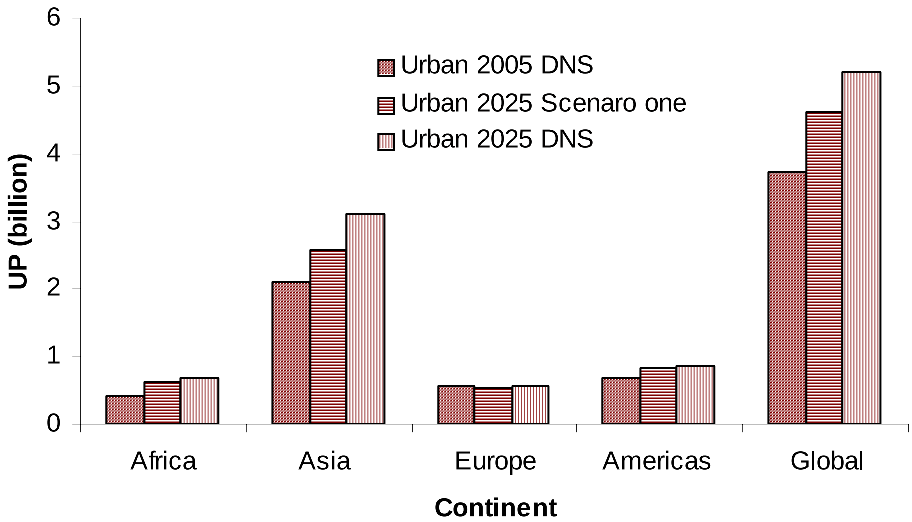

Figure 3.7 Continental and global UP "do nothing scenario (DNS)" and scenario one

CONNECTING STATEMENT TO CHAPTER FOUR

On site composting, within cities of UFW rather than sending UFW to landfills saves money and land and reduces environmental ramifications. Quantification and characterization of food waste (FW) produced in cities need to be evaluated for effective design and smooth operation of urban composting centers.

In this context, chapter four examines characteristic variations of Montreal FW as well as locally available bulking agents to obtain optimum compost recipes for an urban composting center in Montreal.

This chapter is drawn from a manuscript prepared for publication by the author of the thesis and co-authored by his supervisor, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University and Dr. Jose Martinez, Director of Research, CEMAGREF, France. The format has been changed to be consistent within this thesis.

CHAPTER FOUR
VARIATIONS IN CHARACTERISTIC OF FOOD WASTE AND BULKING AGENTS

ABSTRACT

The characterization of food waste (FW) and locally available bulking agents (BA) is a prerequisite to optimizing compost recipe. For downtown Montreal, this study measured the variation in FW characteristics (pH, dry matter (DM), carbon (C), wet bulk density and Total Kjeldahl nitrogen (TKN)) as produced by a restaurant and a community kitchen, from May to August 2004. The project also measured the mass of FW produced by a restaurant and 20 to 48 households, from June to August 2004. Locally available bulking agents were characterized to formulate composting recipes for the summer season. The average residential and restaurant FW production from June to August, in downtown Montreal, was found to be 0.61 (+/-0.13) kg capita^{-1} day^{-1} and 0.56(+/-0.23) kg customer^{-1} day^{-1} respectively. The pH, DM, C and TKN of FW collected from the restaurant and the community kitchen were found to vary from 3.84 to 4.55, 10.01% to 13.73%, 47.4% to 49.3% and 1.69% to 2.67%, respectively, over the summer months. The wet bulk density of the FW varied from 269kg m^{-3} to 552kg m^{-3}. These variations in FW characteristics were found to require the regular adjustment of the composting recipe to insure an efficient process and the planning of a composting facility with sufficient flexibility to handle the 50% variation in mass of FW produced.

The bulk density of chopped wheat straw (CWS), chopped hay (CH) and wood shaving (WS) varied from 16 kg m^{-3}to 127 kg m^{-3}, 43 kg m^{-3} to 109kg m^{-3} and 84 kg m^{-3} to 211kg m^{-3}, respectively, depending upon how much packing pressure was imposed. Because of their high C content, neutral pH and excellent water absorption capacity (WAC), CWS and CH were found to be suitable BA for FW composting whereas WS was found to be acid and the cardboard was found to have poor WAC. Wheat pellets (WP) and animal feed (AF) were found to demonstrate a lack of structural stability once wet.

4.1 Introduction

Finding landfill sites is a growing concern among most cities around the world. Besides the fact that on one wants a waste disposal site in their back yard, landfills use up valuable arable land, because they must offer enough loose soil to daily cover the garbage. Each million persons living in a North American city, produce 0.75 tons of garbage capita^{-1}yr^{-1}, requiring 14 ha yr^{-1} of landfill stacked to a height of 15m (Peavey et al 1985). Thus, a city like Montreal, with 3 million inhabitants, requires 840 ha of landfill site over a 20 year period.

Landfill sites are known to produce leachate that carries both organic and inorganic contaminants (Bou-Zeid & El-Fadel 2004) posing a risk of groundwater contamination (Shin et al 2001). Therefore, landfill leachate must be pumped to the ground surface for treatment. Furthermore, the organic fraction of MSW produces greenhouse gases which must be collected and burnt, to reduce earth warming trend and to eliminate odor nuisances (Peavy et al 1985, Desjardins et Lépine 2002).

Faced with this problem of finding landfill sites, many Canadian cities have introduced recycling management infrastructures. Nova Scotia is the Canadian Province that has reached the highest level of municipal solid waste (MSW) diversion; in 1998, this province banned organic waste from landfill sites, by organizing curbside collection. By 2000, this province was recycling 50% of its MSW (Da Costa et al 2004) while other cities in Canada were following the same trend (City of Toronto 2004, Government of Nova Scotia 2004, Eden 2003). In Quebec, a 50% MSW recycling policy was adopted by the government in 1989, but ten years later, only 10.8% of the MSW stream was being diverted from landfill sites (Environment Quebec 2003). Thus, a new goal of 60% was set to be achieved between 1998 and 2008. Still in 2001, the Communauté Métropolitaine de Montreal (CMM – the Island of Montreal, the North and South shores, Longueuil and Laval) was only recycling 17% of its MSW, with only 7% diversion of the organic wastes (Da Costa et al 2004). In 1991, the City of Montréal estimated that some 24% to 27% of the domestic and commercial MSW were made up of putrescible material, respectively (Ville de Montreal, 1991). In a study conducted at the Macdonald Campus of McGill University, the residential food waste (FW) production was found to range from 0.5 to 0.7 kg person^{-1} day^{-1} (Morin et al 2003).

The implementation of an appropriate waste management treatment system for the City of Montréal requires first of all the characterization of its FW and its rate of production (Green & Kramer 1979, Metin et al 2003, Abu Qdais et al 1997, Diaz et al 1993). For composting, the FW must be characterized for moisture content (MC), pH and C/N ratio (Pace et al 1995, Zucconi et al 1986, Bilitewski et al 1994).

FW has been previously characterized (Table 4.1). For downtown Montreal, Morin et al (2003) have conducted a preliminary investigation to find that the FW produced by grocery stores and restaurants kitchens, including a community kitchen, is quite different from that produced by a university residence. The FW collected from a university residence contained more bread and pasta, as well as paper napkins, which increased the DM and C content, compared to the commercial waste mostly made up of fruits and vegetable waste. In Asia, the FW from a university restaurant was found to be quite different from that of the Canadian University residence (Yun et al 2005). Also, kitchen and household FW collected in South Korea and Taiwan was found to have a MC ranging between 9% and 35%, and a C/N ratio between 10 and 15 (Table 4.1). The characteristics of FW can therefore vary enough from one location to the next, to require a different composting recipe.

The characteristics of different types of FW and of bulking agents (BA) are presented in Table 4.2. Lettuce, onion, tomato and cabbage FW offer a higher N content, compared to potato tops, whole carrot, pepper and bread. The C/N ratio and MC of BA also vary depending on the material used. Wood chips generally offer a very high C/N ratio, and a MC which depends on the degree of drying; the C is mainly composed of lignin and is rather hard to degrade biologically. Wheat straw and hay are reported to offer a lower C/N ratio and a C source that is easier to degrade biologically.

The objective of this chapter was to monitor the quantity and properties of FW produced by a restaurant of the Metropolitan area of Montreal, Canada, from May to August 2004. This monitoring also measured the variation in production rate and properties during the summer. Also, the project characterized some of the locally available BA.

4.2 Materials and Methods

4.2.1 FW quantification

On Tuesday, Thursday and Saturday of every week, from May to August 2004, FW was delivered to a compost center by participating households dwelling the Park Avenue area of the city of Montreal. Some 20, 28 and 41 households participated in June, July and August respectively, and these households had an average family size of 2.5 persons. The FW brought by each household was weighed and recorded.

From June to August of 2004, a downtown Montreal restaurant collaborated in measuring its daily production of FW collected from the kitchen and from the tables. All FW was collected into 100L garbage containers and weighed at the end of every day.

4.2.2 Monitoring the variation in FW production and properties

From mid May to the end of August 2004, FW was collected, sampled and characterized on a weekly basis to observe its variation during the summer months. The FW was produced from a downtown restaurant and a community kitchen that collectively brought their entire FW to the Eco-Quartier composting centre. The FW from both of these businesses was mixed together before sampling, using a tray measuring 1m in diameter and 0.5m in depth. Every collection day, three samples were taken for laboratory analysis, their weight being large enough to represent all types of FW waste collected. The samples thus obtained were homogenized using an electrical grinder and then refrigerated at 5^{o}C until analyzed within one week of collection. The large samples were manually mixed once again before taking duplicate sub samples for various characterization tests.

The characterized BA were those available locally: chopped hay (CH), chopped wheat straw (CWS), wood shaving (WS), rough cardboard (RCB) without a glossy finish, medium rough cardboard (MRCB) with a medium glossy finish, smooth cardboard (SCB) with a glossy finish, wheat pellets (WP) and animal feed (AF). Cardboard was tested as possible bulking agent because of its wide use as packaging material and its massive recovery as recycling material. Hay, straw and wood shavings were also characterized because these are commonly used BA for composting (Alburquerque et al 2005, Barrington et al 2002). The hay and wheat straw had been chopped to a length of 10 to 50 mm while the size of the pine wood shavings ranged between 5 and 40 mm. The animal feed was made up of chopped hay and silages, chopped to a length of 5 mm to 15 mm, and supplemented with grains and minerals. These materials were obtained from the Cattle Research Complex of the Macdonald Campus of McGill University in Montréal. Provided by local grocery stores, the 2 mm to 3mm thick cardboard (RCB, MRCB and SCB) was cut into 20 mm to 30 mm wide strips before usage. The wheat pellets had a particle size distribution ranging between 5 mm and 10 mm.

The FW and BA were characterized for pH, dry matter (DM), carbon (C), nitrogen (TKN), water absorption capacity (WAC) and C/N ratio. Nitrates and nitrites were not analyzed as they represent a very limited fraction of the total nitrogen contained in both fresh FW and bulking agents.

4.2.3 Analytical procedures

Dry matter was determine by drying at 103 °C for 24h in an oven (Scientific John by Sheldon Manufacturing Inc., Cornelius, Oregon, USA) and expressed as:

$$DM\ (\%) = (\text{oven dry sample weight}/\text{wet sample weight}) * 100 \quad (1)$$

The volatile or organic matter portion of these dried samples was determined by burning at 550^0 C in a muffle Furnace (Blue M Electric Company, Blue Island, USA) for 4 hours and expressed as (Haug 1980):

$$C\ (\%) = (100 - \%\ \text{ash})/ 1.83 \quad (2)$$

The TKN (total Kjeldahl nitrogen) was determined by digesting (HACH Digesdahl Digestion Apparatus, USA) the samples with sulfuric acid and 50% hydrogen peroxide at 500 ^{0}C for 15 minutes and measuring the resulting NH_3-N content at a pH of 12, using a NH_3 sensitive electrode (APHA, 1995). Nitrates and nitrites were not quantified as they represent only a very small portion of the total nitrogen content of FW.

The pH was determined using a pH/Ion meter (Orion 450, Boston, USA) and a pH probe. For 24h, a sample of material was soaked in just enough distilled water to be able to produce a solution in which the probe could be placed (APHA, 1995). For the FW waste, 10g of sample was soaked in 20ml of water, while for the dry bulking agents, 50ml of water was needed to soaked 5g of sample.

4.2.4 Determination of wet bulk densities

Affecting the size of the composting facility and maturation center, the wet bulk density of FW was determined immediately after collection, by weighing the mass required to fill a 27 L pail. Varying with compression, the bulk density of BA like straw, hay and wood shavings, was determined using four levels of pressures: loose or without pressure; medium manually compressed and manually compressed obtained by imposing a 0.3 kPa and 0.6kPa pressure to samples contained in a tray measuring 1 m in inside diameter and 0.5m in depth, and; machine compressed corresponding to the density of the material obtained as packaged by the supplier.

4.2.5 Water absorption capacity (WAC) of the BA

The main function of the BA is to provide sufficient dry matter to give a porous structure to the compost mixture and to absorb the moisture produced by the decomposing FW. The water or moisture absorption capacity (WAC) of a BA is therefore an important parameter in the formulation of compost recipes. Soaking the materials in distilled water for 24h, draining off the gravitational water during another 24h under cover to limit evaporation, and then drying at 103 °C for 24h to determine the final moisture content determined WAC values. The WAC (%) was computed as:

WAC (%) = [(kg soaked sample – kg sample before soaking)/kg sample taken]* 100 (3)

4.3 Statistical analysis

Each FW and BA parameter characterized was averaged from six analyses, where triplicate samples were analyzed twice. The standard deviation of the value is reported along with the average using Excel (Microsoft 2003). ANOVA (SAS software, SAS Institute, 1990) was used to compare the FW characteristics between months of production, using a 95% confidence level. All correlation equations and coefficients were obtained using Excel (Microsoft 2003).

4.4 Results and Discussions

4.4.1 FW quantification

The participating households produced, on the average and from June to August 2004, 0.6 (+/- 0.12) kg of FW capita^{-1} day^{-1} (Figure 4.1). Although there were no significant differences in FW production between months, the average FW production in June was slightly lower than that of July and August. This variation is likely due to the availability of lower priced fresh fruits and vegetables in July and August. This amount falls within the range of 0.5 to 0.7 kg of FW capita^{-1} day^{-1} measured by Morin et al (2003). On an annual basis, one person would therefore produce 220 kg of FW and a city like Montreal, with 3 million habitants, would therefore produce 660 thousand tons of FW.

At the restaurant, some 0.55kg of FW customer^{-1} day^{-1} was produced from June to August (Figure 4.2). Although the variation in FW production between months is not significant, the number of clients served per month varied greatly, as only 1910 persons were served in June, compared to 2720 and 2360 persons served in July and August. This 42% and 24% increases in customers in July and August, as compared to June, is likely due to the tourist industry. Thus, in June, the restaurant produced 1.05 tons of FW while in July and August, it produced 1.5 tons and 1.3 tons, respectively. Such variation in FW production has an important impact on the capacity and flexibility of a composting center that must be designed to handle the low and high seasonal production rates.

4.4.2 Variation in FW characteristics

The monthly variation in FW characteristics for that collected from the restaurant and the community kitchen are presented in Figures 4.3a to f. The monthly variations were found to be significant, especially when comparing May to June, July and August, likely because of the availability of fresh lower priced fruits and vegetables.

The C on a dry weight basis (dwb) was found to vary from May to August 2004 (Figure 4.3a). The mean monthly C of 49.3% (+/-0.77%) in May was higher than that of June, July and August at 47.4% (+/-3.05%), 47.8% (+/-0.93%) and 47.9% (+/-0.32%), respectively. The TKN (dwb) of 1.7% (+/-0.11%) in May increased to 2.0% (+/-0.30%), 2.6% (+/-0.46%) and 2.7% (+/-0.79%) in June, July and August, respectively (Figure 4.3b). Thus, the C/N ratio was found to decrease from 29.1 in May to 23.1, 18.4 and 17.9 in June, July and August, respectively (Figure 4.3c). The C/N ratio of FW in the summer (June to August) is balanced enough to be composted without any correction from the bulking agent, while that of May is slightly high compared to that recommended of 20 to 25 for the effective composting of FW (Diaz et al 1993). This implies that FW composting recipes must be adjusted with seasons.

Similarly, the FW pH of 4.6 (+/-0.25) and were found to be the highest and to drop in June, July and August (Figures 4.3d and 4.3e). The FW pH of June, July and August of 4.1 (+/-0.16), 3.84 (+/-0.19) and 3.95 (+/-0.10), respectively, was found to be significantly lower than that of May. The low pH of the FW waste requires the use of a BA, which has a buffering capacity and a more neutral pH of 6.5 to 7.5. Such range provides a better growth environment for bacteria (Diaz et al 1993).

A significant drop in FW DM was observed between May and the other months of June, July and August. While the FW produced in May had a DM of 13.7% (+/-2.47%), that produced in June, July and August had a DM which dropped to 12.2% (+/-2.05%), 10.0% (+/-1.01%) and 10.3% (+/-0.83%), respectively.

The wet bulk density of the FW was found to increase significantly in June to August, as compared to May (Figure 4.3f). In May, the wet bulk density was 269 kgm^{-3} (+/-84) while it increased to 410 kg m^{-3} (+/-92), 510 kg m^{-3} (+/-72) and 552 kg m^{-3} (+/-80), in June, July and August, respectively.

The variation in FW characteristics from May to August resulted likely from the lower priced fresh vegetables and fruits available in the summer, despite the fact that such foods are available all year round. At the beginning of summer, FW was observed to be made up mostly of remains of root vegetables such as potato and carrot peels, of cabbage and of fruits such as apple and citrus fruit peels. As of the end of June, FW was made up of residues from fresh vegetables like tomatoes, lettuce, cabbage, onions, and of fruits such as pineapple, melons, peaches and citrus fruits. By mid summer, the FW contained a higher percentage of TKN and moisture. Along with the fact that restaurants produce more FW in the summer months, their higher MC implies the use of more BA of excellent WAC. Furthermore, these changes in FW properties with seasons impose additional volume flexibility on urban composting systems.

4.4.3 BA characterization

The properties of the BA were found to vary among type (Figures 4.4a to f). In terms of pH, that of wheat pellets (WP) was the highest at 7.5 (+/-0.44), while that of all cardboards (SCB, MRCB, RCB) ranged between 7.2 and 7.7 (+/-0.44); that of chopped wheat straw and chopped hay was 7.0 (+/-0.55) and 6.6 (+/-0.46), respectively, and; that of left over animal feed (AF) and wood shavings (WS) was lowest at 5.9 (+/-0.11) and 5.6 (+/-0.25), respectively (Figure 4.4a). Using the AF or WS along with the acid FW would definitely require some limestone to correct the pH of the compost mixture. Otherwise, some problems can be encountered in reaching thermophilic temperature ranges.

The AF demonstrated the highest TKN value of 3.01% (+/-0.63%), followed by that of WP and CH at 1.40% (+/-0.43%) and 0.89 (+/-0.12%), respectively; and that of CWS at 0.50% (+/-0.08%); that of the cardboards RCB, MRCB and SCB at 0.37% (+/-0.033%), 0.28% (+/-0.011%), 0.22% (+/-0.01%), and; that of WS at 0.08% (+/-0.02%) (Figure 4.4b). Thus, the AF, CH and WP offered the highest nitrogen content as a bulking agent, while the cardboard, the straw and wood shavings offered the least.

The carbon content of the WS, CH and CWS was above 50%, or 54.18% (+/-0.51%), 51.65% (+/-0.56%) and 50.38% (+/-0.95%), respectively, while that of the cardboard (SCB, RCB, MRCB) was 48.42% (+/-0.016%), 48.04% (+/-0.206%), 45.40% (+/-0.16%), and; that of the AF and WP was 44.83% (+/-0.096%) and 42.66% (+/-0.409%) respectively (Figure 4.4c). The lower organic matter content or higher mineral content of AF and WP was reflected by their higher TKN content. Despite these variations, the variability in C biodegradability must also be considered. Although it was not analyzed in the project, it is well known that all wood products (WS and cardboard) have a high lignin content, implying that such BA take some time to decompose and become non recognizable during composting (Diaz et al 1993).

Highest DM values were exhibited by SCB, RCB, MRCB at 95.8% (+/-0.07%), 95.5% (+/-0.12%) and 95.3% (+/-0.18%), respectively, while WP, AF, CH, CWS were moderately dry BA at 92.7% (+/-0.085%), 90.6% (+/-0.70%), 90.8% (+/-1.44) and 88.9% (+/-1.26%), respectively and WS was a relatively wet BA at 78.7% (+/-5.26%) (Figure 4.4d). Except for the WS, all bulking agents had a MC below 85%, which should enable them to better absorb FW moisture.

The highest WAC was obtained with the WP and CWS at 613% and 543%, followed by that of WS, CH and AF at 401%, 366% and 397%, respectively, and that of the cardboard (RCB, MRCB and SCB) at 355%, 329%, and 208% respectively (Figure 4.4e). There was no correlation found between bulking agent DM and WAC, likely because of the different composition of each type of materials. Only that of WP, CWS and WS showed a high correlation of R^2 = 0.99, between DM and WAC, because of similar crop origin, compared to the cardboard and WS being made mostly of wood products treated to a different degree.

Starting with the highest one, the C/N ratios of AF, WP and CH were 15, 32 and 58, while that of CWS was 101, that if the cardboards (SCB, MRCB, RCB) was 223, 160 and 131, respectively. The C/N ratio of WS was lowest at 677 (Figure 4.4f). Only the AF offered a C/N ratio below 25, implying that this bulking agent would not require the addition of nitrogen to obtain a compost mixture C/N ratio between 20 and 25. The WP and CH offered a C/N ratio between 30 and 60, implying a slight correction in the C/N ratio of the compost recipe. The C/N ratio of the wheat straw, cardboard and wood shavings was extremely high, implying the necessary correction of the compost mixture C/N ratio.

The loose, medium manually compressed, manually compressed and machine compressed bulk densities of CWS were 16kg m^{-3}, 38kg m^{-3}, 68kg m^{-3} and 127kg m^{-3}, respectively (Figure 4.5). For CH, loose, medium manually compressed and manually compressed bulk densities were found 43kg m^{-3}, 75kg m^{-3}, 109kg m^{-3} and 169kg m^{-3}, respectively (Figure 4.5). The loose, medium manually compressed, manually compressed and machine compressed bulk densities of WS were found 84kg m^{-3}, 116kg m^{-3}, 151kg m^{-3} and 211kg m^{-3}, respectively. For the range of pressures tested, a linear relationship was observed between compressive pressure and wet bulk density for CWS, CH and WS, respectively:

$$WBD_{CWS}\ (g\ m^{-3}) = 90 * P\ (kPa) + 15.5 \qquad R^2 = 0.99 \qquad (4)$$

$$WBD_{CH}\ (g\ m^{-3}) = 100 * P\ (kPa) + 46.8 \qquad R^2 = 0.99 \qquad (5)$$

$$WBD_{WS}\ (g\ m^{-3}) = 101 * P\ (kPa) + 87.8 \qquad R^2 = 0.99 \qquad (6)$$

Among all BA characterized, CWS were found to be the best demonstrating excellent WAC, a neutral pH and a moderately high C/N ratio. As BA, AF and WS exhibited a low pH, which can lead to fermentation problems when composted with already acid FW. WP was disqualified along with AF, as both BA demonstrated a lack of structural stability once wet. All cardboards were found to have a lower WAC, along with a well-known high lignin content, thus limiting their ability to absorb FW leachate and to provide readily available C to balance the composting recipe.

4.4.4 Changes in compost recipe over the summer months

The compost recipes required to process the FW produced by the restaurant over the course of the summer (May to August) were computed using either CWS, CH or WS as

BA (Tables 4.3 a, b and c). The recipes were computed for an initial C/N ratio of 21 and a DM of 25%. The C/N ratio was corrected by adding NH_4NO_3, as this chemical has relatively no impact on the pH of the mixture, as compared to urea (Barrington et al 2002). The quantities of CWS, CH and WS were computed in terms of volume to size the composting facility.

The volume of the mixture to compost and the quantity of BA required is observed to vary greatly from June to August. Using CWS for example, in June the restaurant FW would require 160kg of BA as compared to 330kg in July; the volume of FW and BA to compost would measure 3.9 m^3, as compared to 6.0 m^3 in July, and; some 10 kg and 15 kg of NH_4NO_3 would be required for each respective month. If CH was used, approximately the same mass of BA would be required, but the monthly volume to compost would decrease to 3.1 m^3 and 5.0 m^3, respectively, for June and July, along with the mass of NH_4NO_3 required which would drop to 8 kg and 12 kg.

Thus, FW production rate and characteristics as well as the BA selected to complete the compost mixture do have an influence on compost recipe. For an efficient process, the FW and selected BA should be regularly characterized.

4.5 Conclusion

This project measured the quantity of FW produced by downtown Montreal households and a restaurant. Also, the FW produced by a restaurant along with that of a community kitchen was characterized on a monthly basis. The quantity, MC and TKN were found to significantly increase from May to August whereas the C/N ratio was found to decrease. Thus, the composting of this FW would require the monthly adjustment of the compost recipe and the design of a composting facility able to accommodate a volume of material fluctuating by as much as 50%.

As BA, CWS and CH were found to offer the best properties, with a high WAC of over 500%, a neutral pH and a moderately high C/N ratio of more or less 50. Wood shavings and AF were found to be acid while WP and AF were found to demonstrate a lack of structural stability after absorbing moisture. All cardboards were found to have a lower WAC, thus limiting their ability to absorb the leachate released by the FW during composting.

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Table 4.1 FW characteristics of different countries

Country	FW producer	pH	DM %	TN (%dwb)	C (%dwb)	C/N ratio	Reference
Canada	Restaurant	3.8-5.2	7-16	5.4-10.7	46-50	4.3-9.2	Morin et al (2003)
Canada	Grocery	4-5	9-15	2.4-16.7	47-50	2.8-20.5	Morin et al (2003)
Canada	University residence	4.6	18	2.2	50	22.8	Morin et al (2003)
South Korea	University Restaurant	-	19.7-20	0.09-6.9	48.4-53.95	7	Yun et al (2005); Kwon & Lee (2004)
South Korea	Household	5-5.4	9.2-32.59	3.13-4.4	48.63-45.9	10.4-15.5	Seo et al (2004)
Taiwan	Kitchen	-	20-35	3-4	50-52	15	Chang et al (2005)

Note: dwb - dry weight basis ; TN – TKN plus nitrate and nitrite-N, where nitrate and nitrites are generally found in quantities relatively low with respect to TKN.

Table 4.2 Characteristic of various organic materials and bulking agents

Materials	pH	%DM	%TN (dwb)	%C (dwb)	C/N ratio	Reference
Lettuce	-	3.8	4.13	42.5	10.3	McGuckin et al (1999)
Onion	-	8.9	3.76	43.3	11.5	McGuckin et al (1999)
Potato tops	-	-	1.5	37.5	25	Gotaas (1956)
Whole carrot	-	-	1.6	43.2	27	Gotaas (1956)
Tomato	-	-	3.3	39.6	12	Gotaas (1956)
Cabbage	-	-	3.6	43.2	12	Gotaas (1956)
Pepper	-	-	2.6	39	15	Gotaas (1956)
Bread	-	-	2.1	-	-	Gotaas (1956)
Wood chips	-	-	0.08	52.24	653	Martinez et al (1999)
Wheat straw	-	-	0.46	42.32	92	Liang et al (1999)
Wheat straw	6.3	86.9	0.98	49.8	50.8	Barrington et al (2002)
Hay	5.2	87.2	1.1	51.1	46.5	Barrington et al (2002)

Note: dwb, dry weight basis

Table 4.3a CWS required for the composting of FW produced by a restaurant in downtown, Montreal, for an initial C/N ratio of 21 and a DM of 25%

Months	FW		CWS					NH_4NO_3
	kg	m^3	kg	m^3 0 pressure	m^3 0.3kPa	m^3 0.6kPa	m^3 Machine compressed	kg
June	981(121)	2.4	187(168)	12	5	3	1.5	10(10)
July	1494(150)	3.0	336(300)	21	9	5	3	15(12)
August	1316(135)	2.4	292(260)	18	8	4.3	2.3	13(13)

Note: Numbers in parentheses, dry weight basis

Table 4.3b CH required for the composting of FW produced by a restaurant in downtown, Montreal, for an initial C/N ratio of 21 and a DM of 25%

Months	FW		CH					NH_4NO_3
	kg	m^3	kg	m^3 0 pressure	m^3 0.3kPa	m^3 0.6kPa	m^3 Machine compressed	kg
June	981(121)	2.4	181(166)	4	2.5	1.7	-	8(8)
July	1494(150)	3.0	327(298)	7.6	4.4	3	-	12(12)
August	1316(135)	2.4	285(259)	6.6	3.8	2.6	-	10(10)

Note: Numbers in parentheses, dry weight basis

Table 4.3c WS required for the composting of FW produced by a restaurant in downtown, Montreal, for an initial C/N ratio of 21 and a DM of 25%

Months	FW		WS					NH_4NO_3
	kg	m^3	kg	m^3 0 pressure	m^3 0.3kPa	m^3 0.6kPa	m^3 Machine compressed	kg
June	981(121)	2.4	214(172)	2.5	2	1.4	1	11(12)
July	1494(150)	3.0	383(307)	4.6	3.3	2.5	1.8	19(19)
August	1316(135)	2.4	333(266)	4	3	2.2	1.6	17(17)

Note: Numbers in parentheses, dry weight basis

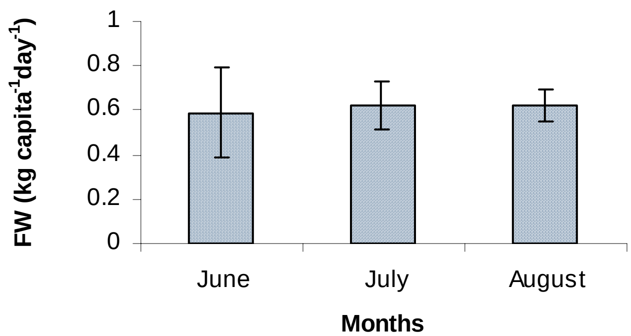

Figure 4.1 Monthly residential FW generation for downtown Montreal

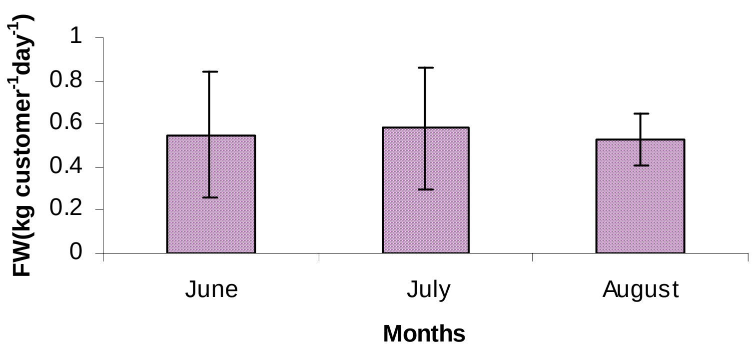

Figure 4.2 Average monthly variation of FW production from one restaurant in downtown Montreal

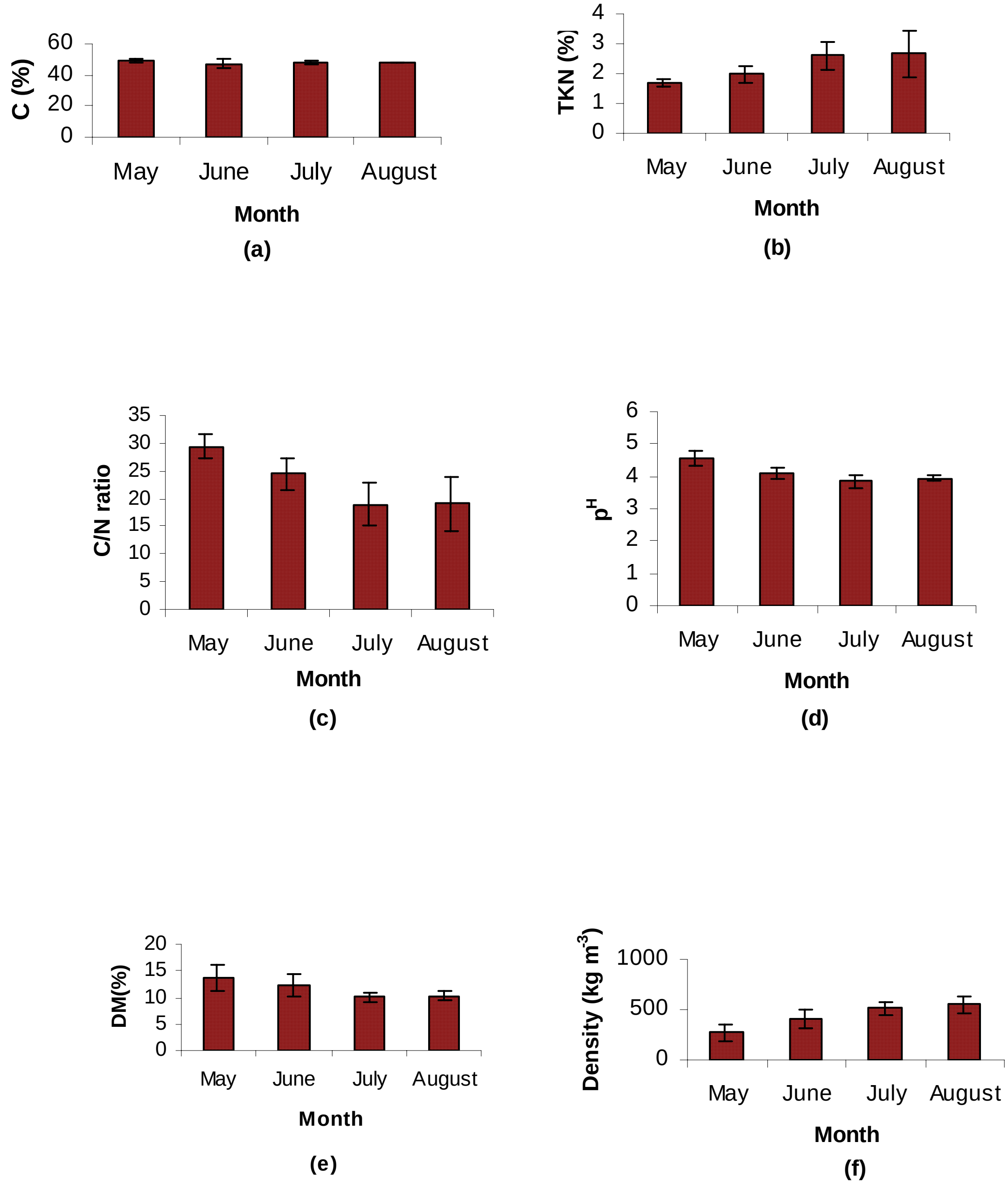

Figure 4.3 Average monthly variations of characteristics of Montreal FW (a) %C (b) %TKN (c) C/N ratio (d) pH (e) %DM (f) density

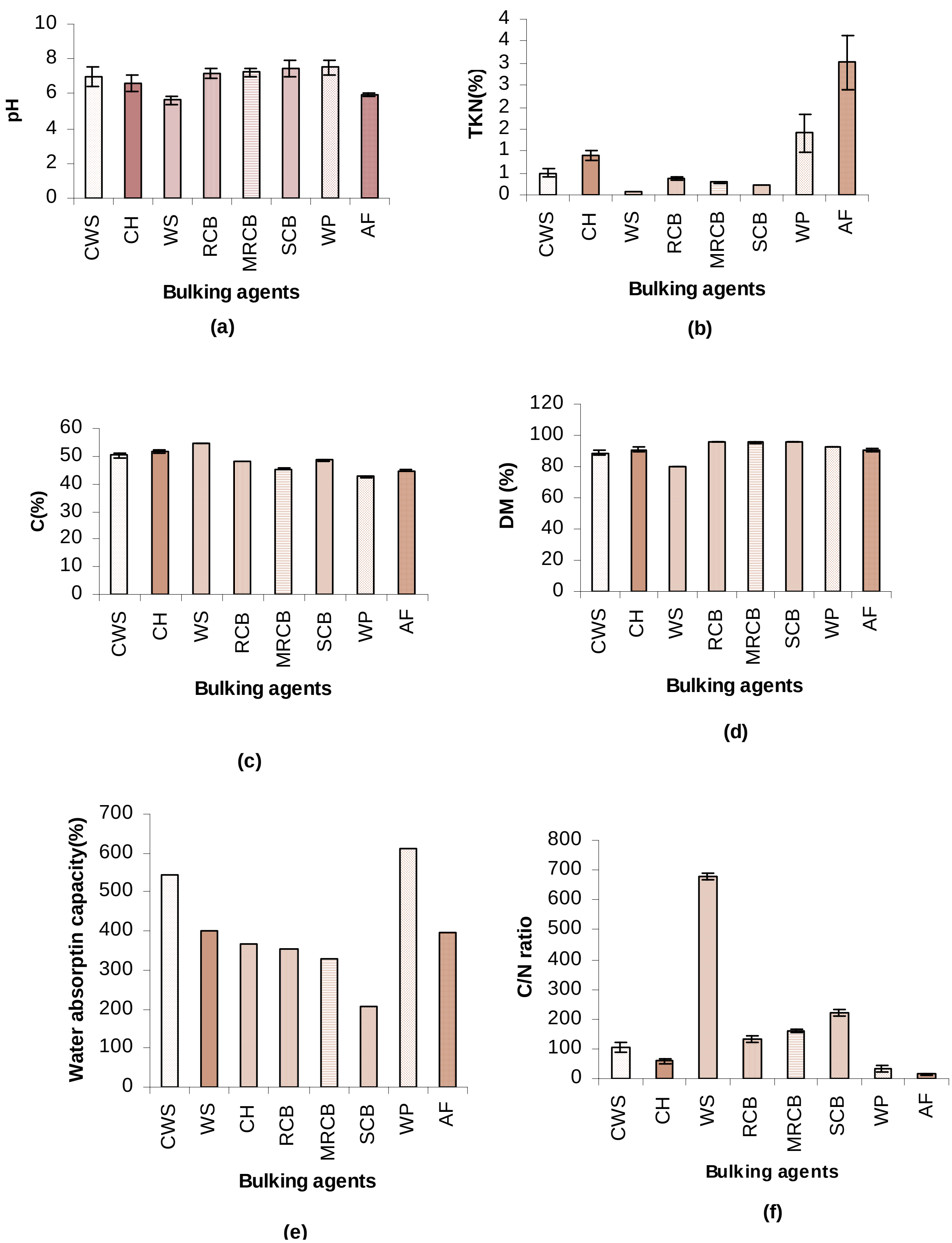

Figure 4.4 Characteristic variations of bulking agents (a) pH (b) %TKN (c) %C (d) %DM (e) Water absorption capacity (f) C/N ratio

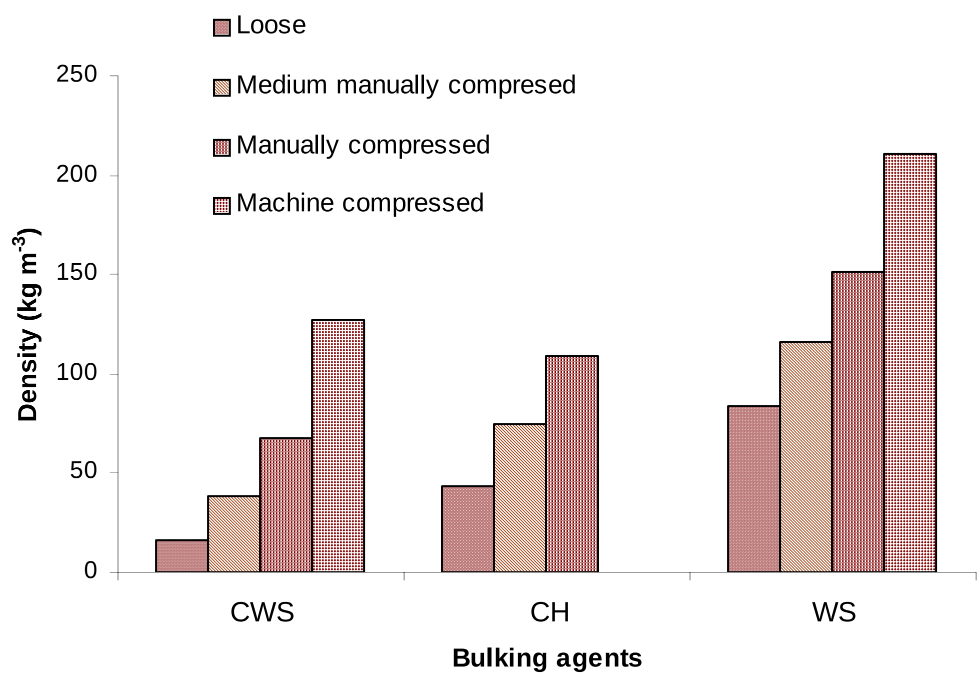

Figure 4.5 Bulk density of bulking agents

CONNECTING STATEMENT TO CHAPTER FIVE

After characterization of FW and bulking agents, various compost recipes were prepared and tested to obtain the best one. Chapter five explains the experimentation and test results of various compost recipes.

This chapter is drawn from a manuscript prepared for publication by the author of the thesis and co-authored by his supervisor, Prof. Dr. Suzelle Barrington, Department of Bioresource Engineering, McGill University and Dr. Jose Martinez, Director of Research, CEMAGREF, France. The format has been changed to be consistent within this thesis.

CHAPTER FIVE
TESTING BULKING AGENTS FOR URBAN FOOD WASTE COMPOSTING

ABSTRACT

Different mixtures of Montreal FW and locally available bulking agents were tested. Each mixture was tested in replication. Chopped wheat straw (CWS), chopped hay (CH) and wood shaving (WS) were used as bulking agents. Six identical urban prototype in-vessel composters with passive aeration system were used. Daily temperature and pH were considered as indictors of level of microbial activities. These indicators were used to compare the performance of each tested recipe.

Keeping initial C/N ratios between 20 to 25, compost recipes were tested with different dry matter (DM) and mix ratios of FW and bulking agents. The NH_4NO_3 was used as an additive to balance the initial C/N ratio of the mixture. The recommended recipes for composting of Montreal FW were 8.9:1 (FW:CWS), 8.6:1 (FW:CH) and 7.8:1 (FW:WS) in wet weight basis. The initial mass of these mixtures was reduced greatly and composts obtained were found suitable for agriculture use.

5.1 Introduction

Composting of urban food waste (UFW) reduces the pressure on municipal solid waste (MSW) management systems and minimizes the environmental ramifications arising from the landfilling of UFW. Composting is a natural process (Barrington et al 2002a) that reduces the volume and mass of solid organic wastes by transforming this waste into a safe soil amendment (Pace et al 1995, Biddestone & Gray 1985, Picci et al 1978, Haug 1980, Cassarino, 1986).

The City of Montreal has encouraged the recycling of components of MSW by instituting in several localities, environmental awareness groups called Éco-Quartiers. Among other activities, these groups have been encouraging citizens to compost their food waste (FW). Unless willing to practice vermiculture, those living in apartment buildings do not have the space to compost their FW using conventional household composters, as placed on apartment balconies, these drip and create a problem for those living below. Éco-Quartier Jeanne-Mance/West End has undertaken to build a community composting center in the Jeanne Mance Park, to accommodate those willing to compost, but without the space to do so. To operate such a community compost center at least cost, Éco-Quartier Jeanne Mance/West End must acquire the proper bulking agents, and use them in adequate quantities.

In a composting recipe, the main contribution of a bulking agent is to correct the moisture of the FW which is often too wet, and which produces further moisture as it decomposes; to act as a pH buffer because of the organic acids initially produced during the composting process; to provide proper aeration by giving the mixture a stable structure and porosity, and; to add some carbon to adjust the C/N ratio within a value of 20 to 25 (Pace et al., 1995, Zucconi et al 1986).

The initial moisture level of a FW and bulking agent mixture should range between 40 and 85% (Zucconi et al 1986, Pace et al 1995, Morin et al 2003). According to Haug (1980), vegetable trimmings were composted by McGauhey and Gotaas by using up to 85% moisture with straw and up to 76% with paper. Fibrous or bulky material such as straw or wood chips can absorb relatively large quantities of water and still maintain their structural integrity and porosity (Haug 1980).

A C/N ratio of 15 to 30 is suggested for an active aerobic metabolism (Haug 1993). A C/N ratio below 20 produces excess ammonia and unpleasant odors while a C/N ratio above 40 does not provide enough N for microbial growth and a fast composting process.

Temperature is considered as a good indicator of the biological activity and composting process. A short mesophilic (25°C to 40°C) followed by a 2 to 3 day thermophilic (over 40°C) temperature regime is sought (Pace et al 1995) for proper stabilization without excessive carbon losses. A high temperature of 55°C -60°C, lasting beyond 5 to 6 weeks, indicates an abnormally prolonged decomposition and a delayed transition to the stabilization stage (Zucconi et al 1986). Sufficient aeration is required to control the temperature and to reduce the amount of putrefactive odors released from the waste during its treatment (Barrington et al 2002b). Three different techniques are suggested for composting natural, passive and active (Fernandes et al 1994). Passive aeration system is considered simple and cost effective for UFW composting compared to active aeration system (Sartaj et al 1997, Haug 1993).

A neutral to slightly alkaline pH range is suggested for optimum microbial activity during composting (Bidlingmaier et al 1985). The pH of organic substrates ranges widely between 3 and 11 (Zucconi et al 1986). The pH is expected to drop at the beginning of composting process, as a result of acid-forming bacteria initializing the process by breaking down complex carbonaceous materials. Later, proteins are broken down and ammonia is liberated producing H^+ ions and increasing the pH (Zucconi et al 1986, Bilitewski et al 1994). The preferred pH for composting ranges between 6.5 and 8.0 (Pace et al 1995).

Bulking agents are expensive composting materials for urban communities as they must be purchased and transported from outside the city. It is therefore imperative, in most composting centers, to properly select and use bulking agents. The main objective of this project was to test different bulking agents for the composting of FW. Three common bulking agents were mixed at three different ratios with FW collected in downtown Montreal. These mixtures were composted using prototype composters and the temperature regime, which developed thereafter, was used to evaluate the effectiveness of the mixture in stabilizing the waste. Temperature regime during the composting process is an excellent indicator of the bacterial activity essential to the composting process (Barrington et al 1998).

5.2 Materials and methods

5.2.1 Experimental installations

Trial tests of compost recipes were conducted by using six urban prototype composters, similar to horizontal in-vessel systems. These prototype composters were built of noninsulated corrugated plastic tubing, 1m in length and 0.3 m in inside diameter (Figure 5.1). A horizontal perforated pipe with openings of 0.5cm diameter at the spacing of 1.5cm was inserted at the bottom of each composter to provide an inlet for air through passive aeration, while the effluent air was allowed to exit from the top end of the composter (Figure 5.1). Each composter was filled to two third capacities with the mixture of FW and bulking agent.

5.2.2 Compost recipes

From the characterization of the FW and bulking agents (chapter four) as presented in Tables 5.1 and 5.2, compost recipes were computed. For each bulking agent selected, for different mixtures were formulated to offer a different moisture level (Table 5.3, 5.4 & 5.5). Each compost mixture was formulated by weighing separately the FW and bulking agent, mixing the two manually in a tray and then before loading the composters. Ammonium nitrate (NH_4NO_3) was added as required by the recipes to balance the C/N ratio between 20 and 25. For the CWS bulking agent, 40%, 35%, 30%, 25% and 20% were tested as initial compost mixture dry matter (DM) (recipe numbers 1, 2, 3, 4, and 5, respectively, Table 5.3). For the chopped hay (CH) and wood shaving (WS) bulking agents, 40%, 30% and 20% were tested as initial compost mixture DM (recipe numbers 1, 2, and 3, respectively, Table 5.4 and 5.5).

5.2.3 Parameters monitored

In this experiment temperature and pH were considered as composting indicators for the testing of UFW recipes. For all recipes tested, the temperature was measured daily using a 1.0m stem compost PTC-Thermometer (model 8500D-II). On alternate days, five 5g compost samples were randomly collected from each composter for pH determination. The collected samples were soaked for 24h, in sufficient distilled water to produce enough liquid to use a pH probe. Generally, the compost samples were mixed with water using a mass ratio of 1:5. The test compost mixtures were started one after the other and in duplicates; this explains why they were not matured over the same time. The leachate production during the process was not analyzed.

When the compost temperature started receding, the composters were emptied to store the compost in vertical plastic bins of size 36cm diameter and 30cm deep rested on wooden blocks with leachate drainage provision from the bottom (Figure 5.2) by allowing natural aeration system for maturation. After 90, 65 and 56 days for FW:CWS, FW:CH and FW:WS respectively, the final mass of the compost was measured and sampled for moisture (MC), organic matter (OMC) and Total Kjeldahl Nitrogen (TKN) content determination (Zucconi & De Bertoldi 1987).

5.3 Results and discussions

5.3.1 Effect of compost dry matter (DM)

For the compost mixtures using CWS, Figures 5.3a and b illustrate the temperature fluctuations obtained as compared to the ambient air temperature. The compost mixtures with a DM equal to and over 30% (FW/BA ratios of 2:1, 2.5:1 and 3.4:1) did not produced thermophilic temperatures as opposed to those with a DM of 20% and 25% which were observed to reach the thermophilic range (50°C) after three days of loading the composters. In figure 5.3b, temperature dropped sharply on fifth day of composting process likely due to the drop of ambient temperature which is as low as 15 ^{0}C.

For the compost mixtures using CH as a bulking agent, thermophilic temperatures were reached after three days of loading, only for the 20% DM mixture (ratio of FW and CH 8.6:1, wet weight basis) (Figure 5.4). The highest temperature reached by the other mixtures was 35°C. For the WS, none of the mixtures reached the thermophilic range. Rather, the highest temperature reached was 35°C (Figure 5.5).

For both the chopped wheat straw (CWS) and hay (CH), a DM of 20% was preferred to that equal to and over 30%. For the wood shavings (WS), a dry matter as low as 20% did not even produce thermophilic temperatures.

5.3.2 The effect of pH

The pH of the mixtures of FW and CWS were found to be slightly acidic at the beginning of the composting process, indicating the production of organic acids (Zucconi et al 1986, Bilitewski et al1994). After three days of composting, the pH increased above

7 (Figure 5.6). The pH of the 20% DM mixture went alkaline only after day 7, as compared to the other mixtures where the pH became alkaline as off day 3. This likely result from the greater percentage of FW, producing organic acids during the initial phase of decomposition.

Using CH as bulking agent (BA), the pH of all mixtures was also found to be slightly acidic at the beginning of the composting process and to increase to a value between 7.0 and 7.6 after three days of loading (Figure 5.7). Again, the time required to observe an increase in pH was related to the amount of BA, likely because higher levels of FW produce more initial organic acids. With WS, the initial pH was quite low, likely because WS exhibit a low pH, and this pH increased to reach over 7, only for the 20% DM (FW/BA ratio of 7.8/1) mixture (Figure 5.8). Among other factors, the low pH experienced with the WS mixtures may explain why thermophilic temperatures were never reached.

5.3.3 Mass reduction of the compost mixtures

The best compost recipe corresponded to the FW and CWS mixture at 20% DM (FW/CWS ratio of 8.9:1, wwb). The fully decomposed texture of this compost material obtained after 90 d of maturation. The 25% DM mixture (FW/CWS ratio of 5:1, wwb) can also be considered, however screening of the final product is recommended because all the materials were not fully decomposed even after 90 d of maturation. Therefore, screening of the final product is essential to remove uncomposted material composed mainly of chopped wheat straw, and to recycle this material as bulking agents.

The texture of the compost obtained after 65d of maturation with the FW and CH mixtures at DM levels of 40% and 30% (FW/CH ratios of 1.8:1 and 3.3:1, wwb) were not fully decomposed whereas a good composted material was obtained with the 20% (FW/CH ratio 8.6:1, wwb) DM mixture.

The texture of the compost obtained after 56d of maturation with FW and WS mixtures of 40%, 30% and 20% DM (FW/WS ratios of 1.5:1, 2.9:1 and 7.8:1, wwb) were found that none of the mixtures decomposed properly, however mixture with 20% DM was found better than the rest. Along with the fact that thermophilic temperatures were not reached in the composters, likely due to acidic nature of the BA (Table 5.2).

Therefore, the chopped wheat straw and hay did produce compost material, which was fully decomposed after two to three, months of maturation. The texture of the wood shaving mixtures was less desirable because of their limited decomposition, a property generally associated with high lignin materials.

The mass reduction of the mixtures during composting and maturation is summarized in Table 5.6, for CWS, CH and WS, respectively. For CWS, the mass reduction of the 40%, 30%, 25%, and 20% DM mixture were found 62%, 70%, 77% and 86% respectively after 90 days (Table 5.6). Most of this reduction resulted from the loss of water, as the final MC was 35%, compared to 75% for the original mixture.

The mass reduction for the CH mixtures is reported in Table 5.6. After 65 days, the mass reduction was found to be proportional to the original MC of the mixture, with the 20% DM loosing the most mass, followed by that with 30% and then 40% DM. Again, water losses account for most of the mass reduction.

The mass reduction for the WS mixtures was as high as that of the other mixtures, again because of water losses. Nevertheless, the WS mixtures were the wettest, after 56d of maturation of mixtures, because of the low temperatures developed during the initial composting stage. The CWS and CH compost mixtures were also found to offer an OM content exceeding 40%, a TKN level exceeding 2.5%, and a phosphorous and potassium level exceeding 0.25% and 3.0%, respectively, on a dry matter basis (Table 5.7). The parameters were found to respect the range required for agricultural use.

In terms of value for agricultural purposes, the 25% and 20% DM mixtures for CWS and CH, respectively, were those experiencing the most mass reduction and reaching a MC of 40% or less, after two months of maturation.

During the course of the composting process, it was observed that the ventilation of the composting material and the leachate collection are important issues. When using drum composters, the material should be turned for 30 minutes, at least once every day for uniform mixing.

5.4 Conclusion

The best compost recipes obtained from the trial tests were 8.9:1 (wet weight basis) of FW & CWS and 8.6:1 (wet weight basis) of FW & CH. The compost obtained from these mixtures was found suitable for agriculture use. The initial mass was reduced greatly. However, the tested mixtures of FW & WS were not fully composted and at the same time temperature could not reach at thermophilic range. Among the tested three mixtures of FW & WS the mixture of 7.8:1 was found better. Therefore, the recommended recipes for composting of Montreal FW were 8.9:1 (FW:CWS), 8.6:1 (FW:CH) and 7.8:1 (FW:WS) in wet weight basis. The provision of leachate collection and aeration system must be insured to achieve the desired level of composting process.

5.5 References

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Table 5.1 Monthly variations of FW characteristics

Months	pH	%DM	%C	%TKN	C/N ratio	Wet bulk density (kgm^{-3})
May	4.55(0.25)	13.73(2.47)	49.25(0.77)	1.69(0.11)	29.3(2.2)	269(84)
June	4.1(0.16)	12.22(2.04)	47.35(3.05)	1.98(0.3)	24.4(3)	410(92)
July	3.84(0.19)	10.01(1.01)	47.77(0.93)	2.6(0.46)	19(3.8)	510(72)
August	3.95(0.1)	10.25(0.83)	47.9(0.32)	2.67(0.79	19.1(4.8)	552(80)

Note: Numbers in parenthesis, standard deviation

Table 5.2 Characteristics of bulking agents

Parameters	CWS	CH	WS
pH	6.96 (0.55)	6.61(0.46)	5.62(0.25)
%DM	88.86(1.26)	90.78(1.44)	79.84(0.18)
%C	50.38(0.95)	51.65(0.56)	54.48(0.02)
%TKN	0.5(0.08)	0.89(0.12)	0.08(0.01)
C/N ratio	103(15.8)	59(8.5)	676(10.9)
Wet bulk density ($kg\ m^{-3}$)			
Loose (no compression)	16	43	84
Medium manually compressed (imposing 0.3kPa pressure)	38	75	116
Manually compressed (imposing 0.6kPa pressure)	68	109	151
Machine compressed (obtained as packaged by the supplier)	127	-	211

Note: Numbers in parenthesis, standard deviation

Table 5.3 Trial recipes of FW & chopped wheat straw (CWS)

Recipe Number	FW:CWS WW	FW:CWS DW	NH_4NO_3 % WW	NH_4NO_3 % DW	C/N	DM %
1	2:1	-	1.8	-	20.2	40
2	2.5:1	1:3.1	1.432	4.1	20.9	35
3	3.4:1	1:2.4	1.15	3.8	20.9	30
4	5:1	1:1.5	0.873	3.5	20.9	25
5	8.9:1	1.2:1	0.592	3.0	20.9	20

Note : WW – wet weight; DW – dry weight

Table 5.4 Trial recipes of FW & chopped hay (CH)

Recipe Number	FW:CWS WW	FW:CWS DW	NH_4NO_3 % WW	NH_4NO_3 % DW	C/N	DM %
1	1.8:1	1:4.31	0.70	1.7	21.14	40
2	3.3:1	1:2.23	0.49	1.6	21.21	30
3	8.6:1	1.12:1	0.29	1.4	21.18	20

Note: WW – wet weight; DW – dry weight.

Table 5.5 Trial recipes of FW & wood shaving (WS)

Recipe Number	FW:CWS WW	FW:CWS DW	NH_4NO_3 % WW	NH_4NO_3 % DW	C/N	DM %
1	1.5:1	1:4.48	2.3	5.7	21.02	40
2	2.9:1	1:2.32	1.5	5.0	21.36	30
3	7.8:1	1.14:1	0.74	3.7	21.36	20

Note : WW – wet weight; DW – dry weight

Table 5.6 Mass reduction (wet weight basis) of test recipes of various bulking agents

FW:CWS	%MR (90d)	FW:CH	%MR (65d)	FW:WS	%MR (56d)
2:1	62	1.8:1	57	1.5:1	26
3.4:1	70	3.3:1	69	2.9:1	40
5:1	77	8.6:1	84	7.8:1	71
8.9:1	86				

Note: Numbers in parenthesis, maturity of compost in days

Table 5.7 Comparison of various parameters of composted test recipes for agricultural value as suggested by Zucconi & De Bertoldi (1987)

Parameters	Suggested	Measured values			
		FW:CWS (90d)		FW:CH (65d)	FW:WS (56d)
		5:1	8.9:1	8.6:1	7.8:1
%MC	<40	35	54	40	66
%OM (dw)	>25	39	42	40	51
%TKN (dw)	>0.6	3.72	3.04	2.6	0.95
%P (dw)	>0.22	0.29	0.24	0.41	0.25
%K (dw)	>0.25	3.09	3.16	3.07	2.9

Note: dw, dry weight; 90d, 56d and 56d maturity of compost in days

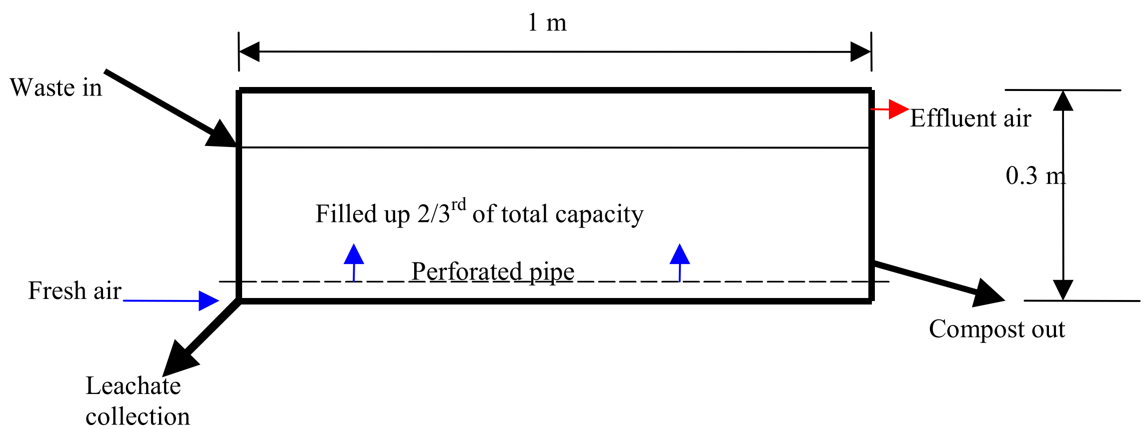


Figure 5.1 Invessel horizontal composter designed for trial test of compost recipes

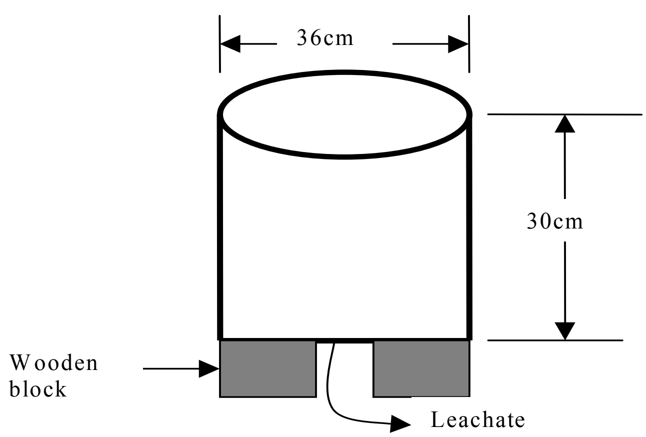
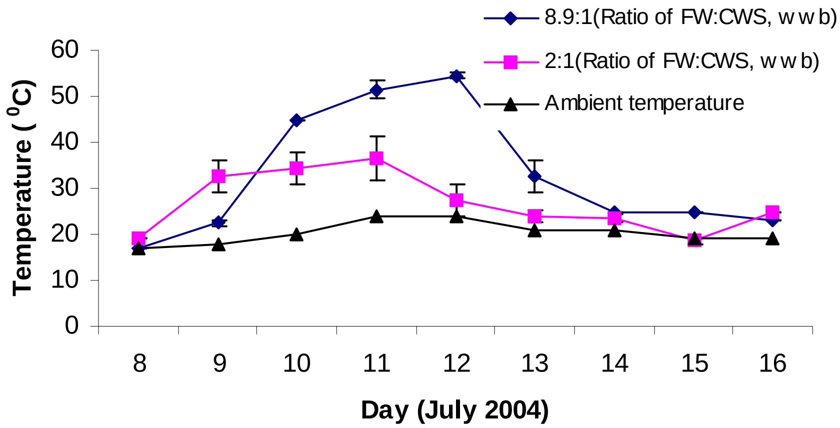
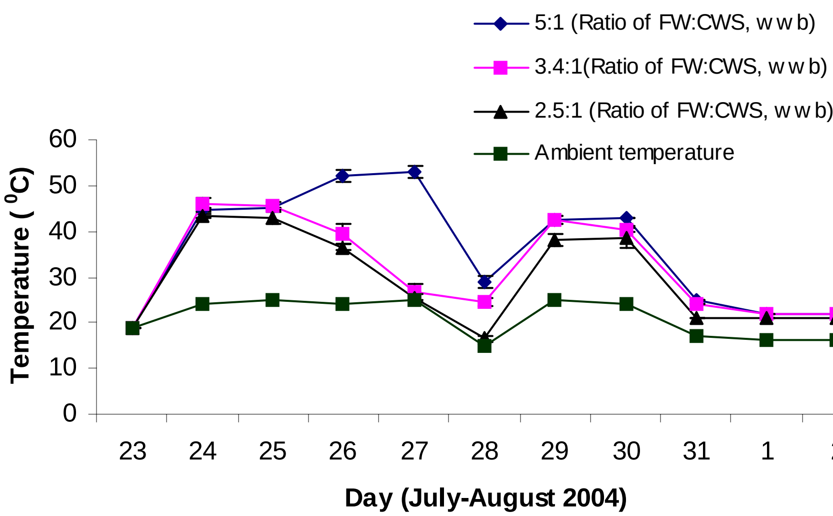


Figure 5.2 Vertical plastic bin, used to store composted test recipes for maturation



(a)



(b)

Figure 5.3 Daily ambient temperature and comparison of daily temperature measured inside compost pile of various mixtures of FW:CWS (a) 8.9:1, 2:1 (b) 5:1, 3.4:1, 2.5:1

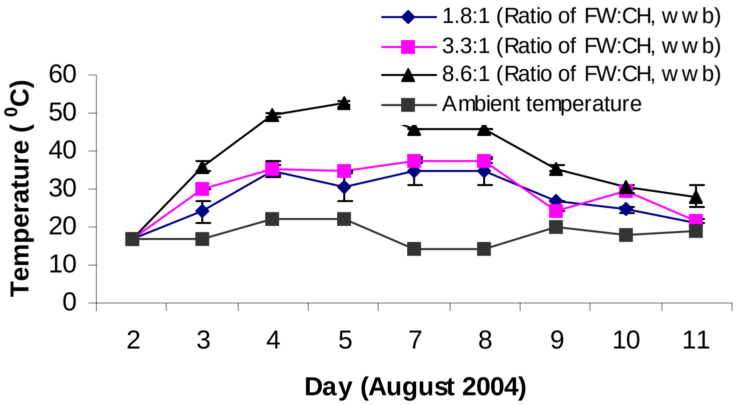


Figure 5.4 Daily ambient temperature and comparison of daily temperature measured inside compost pile of various mixtures of FW:CH

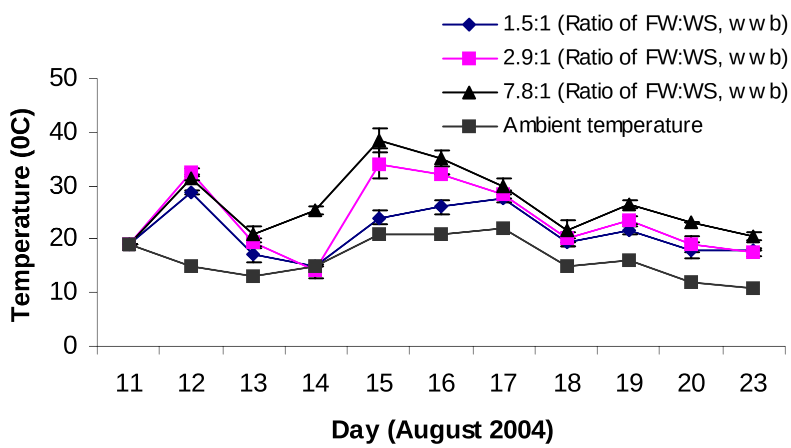


Figure 5.5 Daily ambient temperature and comparison of daily temperature measured inside compost pile of various mixtures of FW:WS

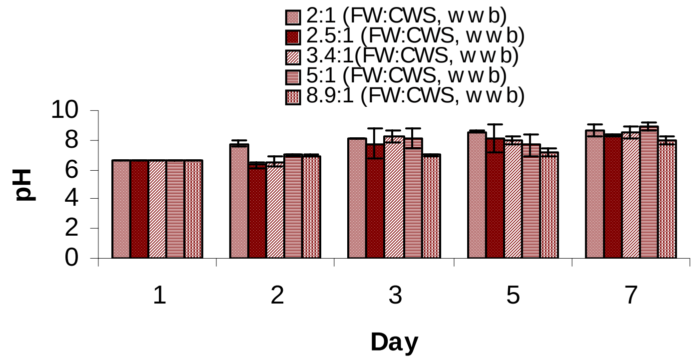


Figure 5.6 pH of various mixtures of FW and CWS during composting process

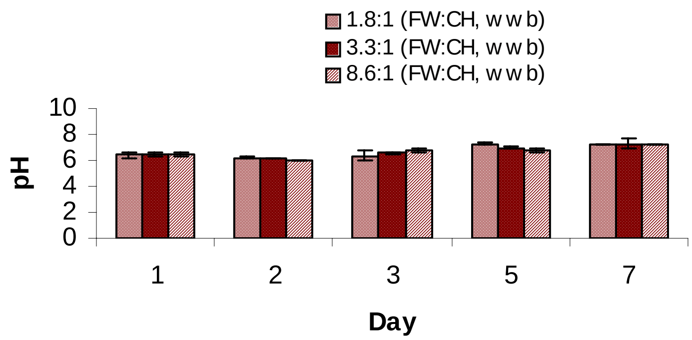


Figure 5.7 pH of various mixtures of FW and CH during composting process

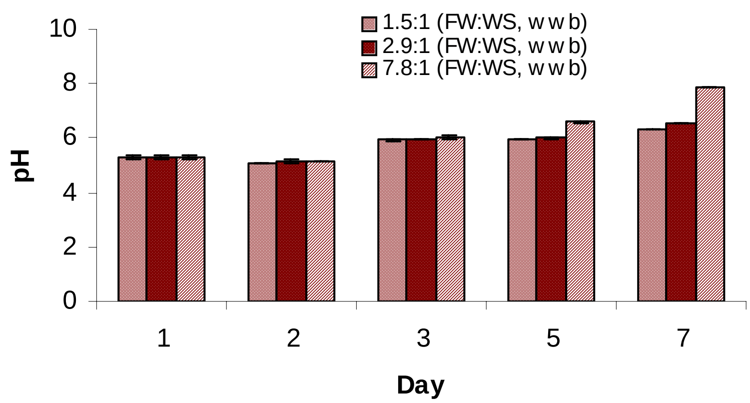


Figure 5.8 pH of various mixtures of FW and WS during composting process

CHAPTER SIX
GENERAL CONCLUSION

The predicted future trends in growing urbanization, economic activities and changing consumption pattern (will) create tremendous pressure on MSW management systems by producing remarkable amounts of FW in big cities around the world. FW not properly managed may have affects both human health and environment and disposal of FW may use limited land resources. Therefore, management of MSW is a great concern for the modern world.

The GDP of a country has a strong influence on growth of urban population and UFW production. Countries having higher GDP produce higher amounts of UFW as a fraction of MSW stream with higher percentage of UP. The growth of world UP in last 30 years was rapid and this trend will continue in developing economy in upcoming decades. The farm gate price of agriculture produce has not gone up in the last 30 years as compared to other goods and services this makes rural economies poorer. Therefore, people from rural areas make their way to cities with the expectation of higher income and better life. If this "do nothing scenario" continues in upcoming decades most of the world cities will face tremendous pressure in their MSW management systems both financially and environmentally. To reduce the pressure on urban waste management system; following solutions are suggested.

(1) Making rural economies more attractive and creating favorable living environment in the rural areas so that there will be no further movement of people from rural to urban areas and

(2) On site aerobic or anaerobic digestion, within the cities, of UFW rather than disposed in landfills.

Composting of UFW is considered one of the best options of on site aerobic digestion. That reduces the load on MSW management systems in developed economies about 20% to 35% and over 50% in developing economy.

However, there are many challenges in building and operating composting facilities in highly urbanized centers like availability of space and bulking agents also odors and leachate require special attention. Therefore, factors affecting composting processes such as moisture, temperature, pH and initial C/N ratio of compost recipe need to be controlled in order to accelerate the process with minimal odor emission and less leachate production. Hence, quantification, characterization of Montreal FW and bulking agents was evaluated for the summer months 2004 and various compost recipes were tested to obtain the best. The quantity and characteristics of Montreal FW were found to vary from one month to another, therefore, compost recipes need to be adjusted regularly for smooth functioning of on site urban composting facilities.

Further in-depth research is needed on urban food waste composting to address the issues like: (1) quantity and composition of food waste in the cities of developed and developing economies (2) testing of compost recipes by mixing food waste with more than one bulking agents (3) quantification of leachate produced during composting process and its potentiality to produce methane from leachate as an alternate source of energy (4) study of potentiality of leachate to use as a liquid fertilizer for crop production (5) study of gaseous emissions like carbon dioxide and ammonia during composting process (6) study of biofilter to treat gaseous emissions during composting process (7) study of mass reduction and quality of stabilized compost and (8) technical and financial evaluation of different aeration systems like passive and active aeration systems during composting process.