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COMPARISON OF HOME-COMPOSTING AND LARGE-SCALE COMPOSTING FOR ORGANIC WASTE MANAGEMENT IN QUÉBEC, CANADA

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SAMMANFATTNING

Hanteringen av organiskt avfall är en stor utmaning för Québec som hittills, deponerat nästan allt sitt organiska avfall. Men att deponera organiskt avfall ger upphov till flera problem: Det producerar metan, en kraftfull växthusgas och lakvatten som kan förorena grundvattnet i närheten av deponier. Dessutom blir deponier snabbt mättade och det blir svårt att öppna nya. För att lösa dessa problem har regeringen i Québec lanserat olika åtgärder för att öka den organiska avfalls återvinningen. Därför måste kommunerna avleda 60% av det organiska avfallet från deponering och återvinna detta.

Syftet med denna studie är att jämföra två lösningar för kommunalt organiskt avfalls återvinning: hemkompostering och storskalig kompostering i kombination med en central kommunal insamling av biologiskt nedbrytbart avfall. I litteraturen har hemkompostering och central kompostering jämförts i termer av utsläpp av växthusgaser (Amlinger et al., 2008) eller mer allmänt, med en jämförande livscykelanalys (Martinez-Blanco et al., 2010). Men det finns få studier som kombinerar ekonomi med strikt miljöaspekt. Denna studie föreslår att en jämförelse görs mellan de två lösningarna med både ekonomiska och miljömässiga aspekter, vilket kan hjälpa en kommun att välja. För detta har två scenarier utvecklats. Dessa jämförs sedan med ett grundscenario där organiskt avfall deponeras. De två scenarierna utvärderades i termer av kostnader, utsläpp av växthusgaser, buller och trafik som genereras från avfall insamling, deponerings livslängd, kompost kvalitet och slutligen, prestanda när det gäller regeringsmål. En fiktiv stad med 50 000 invånare i Québec användes som en fallstudie.

Scenarierna har utformats på grundval av uppgifter som lämnats gällande årligt avfall i Quebec, samt från deltagandet i hemkompostering och kommunal insamling av organiskt material hämtat från litteraturen. Kostnaderna baseras på en intern studie från Chamard et Associés, och utsläppen av växthusgaser från emissionsfaktorer från litteraturen. Andra effekter bedömdes kvalitativt eller direkt från dessa antaganden.

Resultaten visar att i fråga om kostnader, är hemkompostering mer konkurrenskraftigt eftersom det skulle minska kostnaderna med 15 % jämfört med deponering, medan storskalig kompostering tillsammans med en veckas insamling skulle öka kostnaderna med 4%. Storskalig kompostering minskar dock utsläppen av växthusgaser med 240 % medan hemkompostering inte leder till någon minskning alls. Gällande deponiernas livslängd och kompost kvalitet, är storskalig kompostering jämförbart med hemkompostering, medan motsatsen gäller för buller och trafik i samband med sophämtning. Slutligen möjliggör storskalig kompostering att regeringens mål om 60 % återvinning av organiskt avfall kan nås, medan hemkompostering enbart innebär en knapp 40 % återvinning. Andelen deltagande invånare, vilket är högre för den kommunala insamlingen av organiskt avfall än för hemkompostering, är en avgörande prestanda faktor. Därför rekommenderar denna studie att en separat insamling kombineras med storskalig kompostering för att uppnå hög miljöprestanda, trots de något högre kostnaderna. I detta fall måste invånarnas deltagande förbättras genom olika metoder, t.ex. genom utbildning och införande av ekonomiska incitament eller föreskrifter.

SOMMAIRE

La gestion des matières résiduelles organiques représente un gros défi pour le Québec qui, jusqu'à présent, enfouit presque la totalité de ses matières organiques. Or, l'enfouissement des matières organiques pose plusieurs problèmes: cela génère du méthane, un puissant gaz à effet de serre (GES), ainsi que des lixiviats qui peuvent contaminer les nappes phréatiques à proximité des lieux d'enfouissement. De plus, les lieux d'enfouissement sont rapidement saturés alors même qu'il devient difficile d'en ouvrir de nouveaux. Afin de remédier à ces problèmes, le gouvernement du Québec a lancé divers mesures visant à augmenter la récupération des matières organiques. Ainsi, les municipalités doivent détourner 60% des matières organiques de l'enfouissement pour les valoriser.

Le but de cette étude est de comparer deux solutions pour valoriser les matières organiques municipales : le compostage domestique et le compostage centralisé associé à une collecte municipale des matières organiques. Dans la littérature, le compostage domestique et le compostage centralisé ont déjà été comparés en termes d'émissions de GES (Amlinger *et al.*, 2008) ou de façon plus large, à l'aide d'une analyse comparative du cycle de vie (Martinez-Blanco *et al.*, 2010). En revanche, il existe peu d'études qui combinent l'aspect économique à l'aspect strictement environnemental. La présente étude se propose de réaliser une comparaison à la fois économique et environnementale des deux solutions, ce qui pourrait aider une municipalité dans son choix. Pour cela, deux scénarios ont été établis puis comparés à un scénario de référence dans lequel les matières organiques sont enfouies. Les deux scénarios ont été évalués en termes de coûts, d'émissions de GES, de bruit et de circulation générés par la collecte des déchets, de durée de vie des lieux d'enfouissement, de qualité du compost et enfin, de la performance vis-à-vis des objectifs gouvernementaux. Une ville fictive de 50 000 habitants au Québec a été utilisée comme étude de cas.

Les scénarios ont été conçus en fonction des données de production annuelle de déchets au Québec, ainsi qu'à partir de taux de participation au compostage domestique et à la collecte municipale des matières organiques trouvés dans la littérature. Les coûts ont été estimés à partir d'une étude interne de Chamard et Associés, et les émissions de GES à partir de coefficients d'émissions issus de la littérature. Les autres impacts ont été évalués de façon qualitative ou directement à partir des hypothèses.

Les résultats montrent qu'en termes de coûts, le compostage domestique est plus intéressant car il baisserait les coûts de 15% par rapport à l'enfouissement, alors que le compostage centralisé couplé à une collecte hebdomadaire augmenterait les coûts de 4%. En revanche, le compostage centralisé permet de diminuer les émissions de GES de 240% alors que le compostage domestique n'entraîne pas de réduction. En ce qui concerne la durée de vie des lieux d'enfouissement et la qualité du compost, le compostage centralisé se compare favorablement au compostage domestique tandis que c'est l'inverse pour le bruit et la circulation associés à la collecte des matières résiduelles. Enfin, le compostage centralisé permet d'atteindre l'objectif gouvernemental de 60% de récupération des matières organiques, tandis que le compostage domestique permet d'en récupérer à peine 40%. Le taux de participation, qui est plus élevé pour la collecte municipale des matières organiques que pour le compostage domestique, est un élément décisif dans le calcul de la performance. Ainsi, cette étude recommande d'instaurer une collecte séparée suivi du compostage centralisé afin d'obtenir des performances environnementales élevées, malgré la légère hausse des coûts que cela implique. Dans ce cas, il faut s'assurer de la participation des citoyens par divers moyens comme l'éducation, la formation et la mise en place de mesures incitatives financières ou réglementaires.

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ABSTRACT

The management of the organic fraction of municipal solid waste has become a major issue lately in the province of Québec, Canada. Most of it is landfilled today, which increases the burden on landfills and is environmentally unsound. In order to comply with new government guidelines, municipalities have to develop solutions to recover and recycle organic waste. In this context, this study examines two solutions for treating organic waste: home-composting and a separate biodegradable waste collection system combined with large-scale composting. The two scenarios are compared in terms of costs and environmental performance to a reference scenario where all waste is landfilled, using as a case study a fictional city of 50 000 inhabitants. Results indicate that a centralized collection system, combined to large-scale composting, has greater environmental benefits than home-composting. It cuts greenhouse gas emissions by 240% compared to the reference scenario, while emissions from home-composting remain at the reference level. However, when compared to the reference scenario, home-composting reduces waste management costs by 15% while they represent an increase of 4% with large-scale composting. The study concludes that separate biodegradable waste collection combined to large-scale composting is the best way for a municipality to achieve high environmental goals, despite a slight increase of municipal costs. The participation rate of citizens is suggested to be a crucial parameter for the success of organic waste management in the two scenarios and it should be enhanced by different means to ensure the successful implementation of the chosen solution.

Key words: Greenhouse gas emissions; Home-composting; Landfilling; Large-scale composting; Organic waste.

1. INTRODUCTION

1.1. Problem statement

The Canadian province of Québec is facing a great challenge in the field of waste management. Although recycling is growing, the quantity of waste thrown away in landfills is not declining due to the ever increasing amount of waste generated.

In order to reduce the amount of waste ending up in landfills, the government of Québec introduced a new policy, the *Québec Policy on Waste Management 1998-2008* in 2000, which set ambitious goals in terms of recycling. For instance, it required 80% of paper and 60% of plastic, metal and glass to be recycled, and 60% of organic waste to be recovered (MDDEP, 2000). The target is almost fulfilled for recyclable materials, but it is unfortunately far to be met for organic waste. Only 12% of organic waste was recovered in 2008 (Recyc-Québec, 2009a). Yet, organic waste represents 44% of the trash bag in Québec (Recyc-Québec, 2009b).

Organic waste can be treated through composting or anaerobic digestion, producing valuable end-products such as compost or biogas. Instead, this recoverable waste is often condemned to landfilling, which emits methane when decaying, a highly potent greenhouse gas, and leachate that contaminate groundwater.

To prevent those problems, the government of Québec has set several measures towards sustainable organic waste management in its *Action Plan for 2011-2015* (MDDEP, 2011). For instance, the government has invested in organic waste treatment facilities and established guidelines on spreading fertilizers made from organic waste. Landfill taxes were raised in order to discourage landfilling and most importantly, landfilling of organic waste is to be banned by 2020.

At the local level, the municipalities need to take action to reach the 60% target of organic waste recovery and anticipate the future ban on landfilling. To tackle this challenge, they can choose between two strategies: encourage source reduction through home-composting, or introduce a separate, town-controlled biowaste collection scheme using either composting or anaerobic digestion technology. For a municipality, the best solution has to combine a high environmental performance along with the lowest costs possible.

1.2. Aim of the study

The purpose of this study is to compare home-composting and large-scale composting as organic waste management strategies and, by this way, help with the planning of organic waste management at the city's level. It is a tool intended for use by municipalities in Québec for making strategic decision with organic waste management.

Therefore, in this thesis, two scenarios are designed (home-composting and large-scale composting) and compared to a reference scenario that represents what is done today, i.e. landfilling. The scenarios are assessed in terms of costs, environmental impacts and performance regarding government targets.

Finally, this thesis recommends which scenario is best for a municipality to tackle efficiently organic waste management and gives some suggestions on how to implement the scenario successfully.

2. COMPOSTING AS ORGANIC WASTE MANAGEMENT – LITERATURE REVIEW

This chapter gives an overview of the literature reading done during the thesis. Firstly, the process of composting is described, and then the state-of the art in the field is presented, mainly concerning greenhouse gas emissions from composting. Finally, it explains how the thesis will increase knowledge on the topic.

2.1. Theory of composting

2.1.1. *Definition*

Composting is a biological process which enables, under aerobic conditions, the decomposition of organic waste by microorganisms. It produces compost, a stabilized end-product rich in organic matter which can serve as fertilizer and soil amendment (Williams, 2005).

2.1.2. *Composting process*

The composting process can be divided into 4 different stages (Stypka *et al.*, 2005; Williams, 2005):

Preparation includes the shredding and homogenisation of the biodegradable waste.

Composting is the main process and consists in the degradation of the biodegradable waste under aerobic conditions. It starts with a mesophilic stage characterized by medium temperatures and rapid breakdown of biodegradable waste, and is followed by a thermophilic stage with high temperatures and destruction of pathogens. Finally, there is a maturation stage distinguished by low temperatures and decreasing biological activity. The composting process might take from a few days to a couple of months, depending on the technology used (see 2.1.4).

Curing is an essential stage to decompose cellulosic materials which are more difficult to break down. This step may take several months.

Finishing involves sieving of the compost in order to remove contaminants and off-size material and the final product grading.

2.1.3. *Key parameters*

During composting, carbon compounds present in biodegradable waste are degraded by various microorganisms. The microorganisms require a specific environment to reach a high level of activity, including the following parameters (Williams, 2005):

Minimum oxygen content of 18%: The minimum oxygen content ensures aerobic conditions. In order to maintain sufficient oxygen in the compost, it has to be aerated. Depending on the scale, it can be done manually, with turning machine or via more complex aeration systems such as a perforated pipe inside the compost pile.

Temperature of 30-35°C: In order to maximize biological activity, temperature should rise in the compost heap. It occurs naturally in large compost heaps but in home-composters, temperature remains often limited which slows down the composting process.

Minimum moisture content of 40%: Moisture is essential to bacteria which cannot live without water. However, too much water in the compost blocks the oxygen circulation.

pH between 5,5-8: A pH out of this range would threaten biological activity.

C/N ratio of input material around 25: A suitable C/N ratio is important because a higher ratio will slow degradation while compost with a lower ratio will produce bad smell. A way to reach a good C/N ratio is to mix carbon-rich material, such as branches and paper with nitrogen-rich material like food waste and fresh grass.

Suitable porosity of input material: Input material should have a small size in order to increase the surface area and thus enhance decomposition, but it should not be too small otherwise it will block oxygen circulation.

2.1.4. *Different composting systems*

Composting can be done at different scales: at a household level, at a community scale and at a large-scale in a composting plant.

Home-composting

This type of composting can be done very easily at home, as long as there is enough space outside to install the composter. The composter can be installed in the garden or on a balcony. A home-composter is a simple box, made of wood or plastic that can even be home-made. It has a lid to prevent rodent and other animals from eating the compost feedstock, and is in contact with soil to enhance biological activity (Fig. 1).

In general, yard trimmings, preferably shredded, and food waste can be added to the composter. Nevertheless, a few restrictions on what kind of organic waste should be put in the composter must be observed. Meat, fish, dairy products and sanitary material (e.g. diapers) are to be avoided because they are likely to attract vermin. Another reason is that the temperature in the compost heap is usually too low to kill potential pathogens present in such waste and contamination must be avoided (NOVA Envirocom, 2006).

Figure 1: Simple wooden home-composter, with a lid, placed directly on the ground.

Community composting

Community composting, like home-composting, is an on-site treatment. The capacity of a community composter is larger than a home-composter and it can be more sophisticated: the composter might have a forced aeration system or be automatically turned on. It might also have an odor-control system as well as a leachate collection system (Urbaniterre).

Community composting can be done at a school or for a neighborhood. The kind of waste allowed in a community composter is similar to home-composting (Urbaniterre).

Large-scale composting

At a larger scale, a centralized composting plant enables to treat organic waste for a whole city. It requires organic waste to be source-sorted at home and then collected as a separate fraction. A centralized composting plant allows all kinds of organic waste to be treated, including meat and fish. Indeed, the temperature in the compost piles is higher because of the larger quantity of waste treated, so potential pathogens cannot survive. However, some places do not accept diapers in the separate collection.

A composting plant can use different methods (Williams, 2005):

The **windrow system** is the simplest method: Organic waste is stored into long static piles that are periodically aerated by mechanical turning.

In the **forced aeration system**, instead of turning the piles, air is blown through the compost pile via a perforated pipe, thus allowing a continuous aeration.

In-vessel systems are the most sophisticated processes. They are enclosed systems such as a tunnel or drum and they allow control over the process key parameters: temperature, moisture and aeration. In-vessel systems are very often equipped with a biofilter to treat exhaust gases.

2.2. Greenhouse gas emissions from composting

Composting is recognized as an environmentally-friendly way to treat the biodegradable fraction of municipal solid waste (MSW), and as a promising substitute for incineration and landfilling. Nevertheless, it is important to demonstrate that composting is actually a good alternative in term of environmental performance.

A few studies have been aiming at providing reliable data about greenhouse gas (GHG) emissions from composting. Emissions to consider for composting include upstream emissions from collection and transport of waste; operation emissions, i.e. methane and nitrous oxide emitted during the process; and downstream emissions resulting from the application of compost in the soil.

2.2.1. *Upstream emissions*

Emissions from collection, transfer and transport of waste have been investigated by Eisted *et al.* (2009). Emissions from different collection systems have been quantified, such as kerbside and bring collection schemes, or transport by private cars. Emissions are expressed as a global warming factor in kg CO_2-equivalent per ton of wet waste (ww) collected.

2.2.2. *Operation emissions*

Amlinger *et al.* (2008) have produced one of the most comprehensive studies about emissions occurring during the composting process. Many trials have been performed for home-composting as well as large-scale composting, both open and enclosed systems, and for different feedstock. The results present average emission factors for large-scale composting and home-composting, depending on the method and the feedstock. Results show that home-composting could generate higher emissions per ton than large-scale composting. At the same time, these authors assessed the efficiency of a biofilter to treat exhaust gases from the compost pile and concluded that it only had little influence on methane levels and could even enhance the production of nitrous oxide which should be avoided. Another study by Andersen *et al.* (2010) focused on emissions from home-composting only. Six composters were evaluated and results were in line with those from Amlinger *et al.* (2008). The effects of the waste load and the mixing frequency were also assessed. Consistent with the previous studies, the Guidelines for National Greenhouse Gas Inventories by the IPCC (2006) proposed default emission factors for methane and nitrous oxide during composting.

Some studies did not consider GHG emissions during the composting process, either because they could not detect them (e.g. Colon *et al.*, 2010; Smith and Jasim, 2009), or because they assumed them to be negligible (e.g. US Environmental Protection Agency (EPA), 2006). In those cases, aerobic conditions are supposed to be perfectly met so that no methane is formed thanks to sufficient aeration. Another reason is that methane formed in anaerobic pockets is assumed to be immediately oxidized into carbon dioxide (Smith and Jasim, 2009). However, since it was shown by several studies that methane and nitrous oxide are actually emitted during the process of composting (Andersen et al., 2010; Amlinger et al., 2008), it was decided to include those emissions in the present study as discussed later in the methodology.

2.2.3. *Downstream emissions*

Finally, there are very few studies that assess emissions resulting from the application of compost in the soil. Indeed, negative emissions are achieved through the long-term binding of carbon in the soil or through the replacement of synthetic fertilizer or growth media. Boldrin *et al.* (2009) showed that emissions varied greatly depending on the end-use of the compost. The highest emission savings were obtained when compost was used as a substitute for peat, which requires a lot of energy to be extracted. To a lesser extent, emission savings were also measured when compost was used for replacing synthetic fertilizer. The US EPA (2006) also quantified net emission savings from application of compost in the soil. As the literature on the topic is scarce and the final use of the compost is often not well-known, many studies do not take this aspect into account (Colon *et al.*, 2010; Martinez-Blanco *et al.*, 2010). Besides, it is difficult to apply the previous results to home-composting because it is not possible to account for what compost is replacing in each household (Boldrin *et al.*, 2009).

2.2.4. *Life-cycle analysis of composting*

Partially based on those results, recent LCAs (life-cycle analysis) have been conducted on composting. Björklund *et al.* (2000) assessed different scenarios for biodegradable waste management in Stockholm, including large-scale composting. Those scenarios were compared to a reference scenario in which incineration and landfilling prevailed. Björklund *et al.* (2000) found that the composting scenario compared favourably with the reference scenario, especially for the impact on global warming which reached a potential reduction of 100%. Colon *et al.* (2010) and Martinez-Blanco *et al.* (2010) have performed LCAs for home-composting. In both studies, the system boundaries included the manufacture of the composter and associated tools, water and electricity used by the process and greenhouse gases (GHG) emitted during the composting process. Unlike Colon *et al.* (2010), Martinez-Blanco *et al.* performed a comparative LCA in which home-composting was compared to large-scale composting. In their study, home-composting had a greater impact on global warming because methane and nitrous oxide emissions were higher. Conversely, large-scale composting impacted more on other categories such as ozone layer depletion and cumulative energy demand because of higher energy requirements.

It is important to note that Björklund *et al.* (2000) took into account the final use of the compost in their analysis while other studies did not include this aspect (Colon *et al.,* 2010; Martinez-Blanco *et al.,* 2010). It is nevertheless important to consider the final use of compost as it might result in carbon savings with respect to global warming when carbon is sequestrated into the soil, or when compost replaces chemical fertilizers (Boldrin *et al.*, 2009).

2.3. Towards a comprehensive approach to composting

Although there is no consensus about accurate values for GHG emissions from composting, there are nevertheless many recent studies which cover the topic, as discussed earlier. However, when it is time to make a strategic decision about waste management, not only the environmental aspect will be considered but also the economic dimension. In this respect, very few studies assess the potential of composting from a holistic perspective, i.e. by assessing the environmental performance along with the economic feasibility. Adhikari *et al.* (2010) tackled this problem in their study about the potential of home and community composting in Europe and Canada. Home and community composting were compared to large-scale composting and landfilling in terms of costs, greenhouse gas emissions and land use. The results were compiled for the whole of Canada and the whole of Europe.

However, although the study gives interesting inputs on the economic and environmental benefits from implementing home and community composting at a country's scale, it must be kept in mind that waste management planning is not done at the national scale. Instead, local planning authorities have the mandate to implement waste management strategies. Therefore, in order to help local authorities in waste management planning, the present project work assesses the potential for composting (home and large-scale composting) from a holistic perspective and at the city' scale.

3. METHODOLOGY

The methodology of this thesis consists firstly in building two scenarios representing two different ways of dealing with organic waste, basing it on scientific literature and official reports from Canada and Quebec institutions. Secondly, economic and environmental impacts of the two scenarios are evaluated in comparison to a reference scenario.

3.1. Definition of the scenarios

In order to assess the impacts of a municipal biowaste policy, two scenarios, as well as a reference scenario are designed. The reference scenario constitutes the "zero-action on biowaste" scenario, while scenarios A and B represent two alternatives for a municipality that wants to tackle the biowaste issue actively. Scenario A puts more emphasis on source reduction through home-composting, whereas scenario B has a more centralised approach through separate collection and large-scale composting. These scenarios have been set up from investigating case studies and pilot projects, as explained below. They try to reflect reality and not overestimate the quantities that might actually be diverted from landfilling.

In these scenarios, organic waste is divided into two categories: food waste and garden waste. Food waste includes fruit and vegetable leftovers and food scraps, while garden waste consists of leaves, branches and grass.

Table 1: Proportion of waste handled by the three waste management strategies considered.

	Reference Scenario		Scenario A - Home-Composting		Scenario B - Large-scale composting	
	Food waste	Garden waste	Food waste	Garden waste	Food waste	Garden waste
Landfilling	100%	100%	80%	20%	50%	20%
Home-Composting	-	-	20%	20%	-	-
Large-scale composting	-	-	-	60%	50%	80%
Total	100%	100%	100%	100%	100%	100%

Table 1 summarises the proportion of organic waste handled by each strategy in the three scenarios and the hypotheses are justified below.

3.1.1. *Reference Scenario*

100% of organic waste is collected with garbage and then disposed of in a landfill.

This scenario represents what is done today and serves as a baseline to compare the two other scenarios.

3.1.2. *Scenario A: Home-composting*

20% of organic waste is handled by home-composting; seasonal collection of garden waste enables to collect 60% of garden waste; the rest is collected with garbage and landfilled.

The proportion of organic waste diverted from landfill through home-composting is not easy to estimate. It depends on many factors such as access to a backyard, the type of residence, the level of environmental concern, the knowledge of composting and the attitude towards potential inconveniences (Edgerton *et al.*, 2009). In 2006, 27% of Canadians households were composting, but only 13% of them in Québec (Statistics Canada, 2006). Moreover, there are restrictions on inputs for home-composting. For instance, meat, fish and dairy products as well as sanitary products must not be put in home-composters (Compost Council of Canada). A 3-year research program in UK has shown that a capture rate of 20% of biodegradable waste could be achieved (Smith and Jasim, 2009). Therefore, a capture rate of **20% for both food and garden waste** has been chosen for scenario A.

In order to fit better reality, a seasonal collection of garden waste has been incorporated. The seasonal garden waste collection usually takes place between May and October and can involve 2 to 8 collections depending on the size of the municipality. Several municipalities in Québec have set up such a system in order to divert garden waste from landfills and comply with government guidelines (Chamard et Associés, unpublished data). We assume that people who do not compost at home take part into this system because it is often forbidden to throw garden waste with garbage. It is then assumed that **60% of garden waste** is diverted from landfill through garden waste collection.

3.1.3. *Scenario B: Large-scale composting*

A separate collection of organic waste enables to collect 80% of garden waste and 50% of food waste that are then turned into compost at a composting facility; the rest remains collected with garbage and goes to landfilling.

When implementing a separate collection for biodegradable waste, it might be expected that 100% of biodegradable waste is collected, but this is not realistic. It depends on the level of commitment from the participants. According to Recyc-Québec (2009b), the average diversion rate for the municipalities involved in separate biowaste collection is 78%. However, what is mostly found in a biowaste collection is garden waste, especially in spring and autumn (Chamard J.L., Chamard et Associés, personal communication). Indeed, many municipalities that have implemented a weekly collection for biowaste reduce collection frequency to every month during winter, when the waste load is lower. If it can be assumed that 80% of garden waste is collected (Recyc-Québec, 2009b), few studies actually calculate the proportion of food captured by a separate collection of organic material. A survey in UK reported a capture rate of 43% to 77% on different trials, with an average of 59%

(WRAP, 2009). Considering the recentness of separate organic waste collection in Québec, the capture rate in Québec is likely to be in the lower range. Besides, although more waste is accepted in the collection system compared to home-composting, diapers and other sanitary products are still not allowed. Those constraints contribute to lower the capture rate of organic material. Therefore a capture rate of **50% for food waste** is considered while **80% of garden waste** is assumed to be collected in scenario B.

3.1.4. *Case study*

In order to assess the impacts of the three scenarios at a municipality's scale, it was decided to apply the scenarios to a fictional city of 50 000 inhabitants. This choice can be justified as follows: a city of 50 000 inhabitants is in the range of a "medium-sized city" in Québec (between 20 000 and 60 000 inhabitants) (Bruneau, 1989), and for a city at such a size, it has to address the question whether a separate collection for organic waste is needed.

To know the amount and composition of organic waste generated by a municipality in Québec, general data for the province of Québec have been used. According to Recyc-Québec (2010) a person in Québec generates **184 kg** of organic waste per year, among which **31% is garden waste**, 47% is food waste and 22% is other organic waste. Other organic waste refers to paper towel, diaper, tissues. In this study, it has been incorporated into **food waste**, making it **69%** of organic waste.

3.2. Economic impacts

The economic impacts of the three scenarios have been estimated from a municipal perspective. It estimates how much a municipality would pay if it was to choose a private company to implement one of the three scenarios. The data stem from an internal study that I conducted in parallel at *Chamard et Associés* that deals with waste management costs in the province of Québec (Chamard et Associés, unpublished data).

This study gathers the costs entailed by waste management in the 100 largest towns in Québec, a sample of 82% of the population of Québec. Those costs are then classified according to waste flow (garbage, recyclable waste and organic waste) and normalized per household and per ton.

Table 2: Costs per ton associated to the three waste management strategies considered (expressed in CAD ($)/ton).

	Cost ($/ton)			
	Collection and transport	**Disposal**	**Subsidy and communication**	**TOTAL**
Landfilling	80.00	65.00	0.00	**145.00**
Home-composting	0.00	0.00	50.00	**50.00**
Large-scale composting	92.00	63.00	n/a	**155.00**

This thesis investigates average costs for each strategy of organic waste management. The costs of collection and transport are reported separately from treatment costs.

The cost of home-Composting has not been investigated in the study by Chamard et Associés (Chamard et Associés, unpublished data) but has been evaluated in this project work as follows:

For organic waste handled by home-composting, neither collection and transport costs, nor any disposal cost apply because the waste is handled in situ. However, a common way to promote home-composting for a municipality is to subsidize the purchase of home equipment. Many municipalities offer to pay 50% of the composter, while others sell composters at a lower price than market value. A survey made for several municipalities in Québec (Blainville, Boucherville, Gaspé, Laval, MRC Sept-Rivières) indicates an average subsidy of $35 per composter. Given that a composter treats on average 100 kg of organic waste every year and that it has a life-time of 10 years (SOLINOV, 2006), it can be inferred that home-composting costs $35 per ton of treated waste. When training and communication campaigns are taken into account, the cost for home-composting reaches $50 per ton (SOLINOV, 2006).

Table 2 summarizes the costs per ton for the three strategies.

3.3. Greenhouse gas emissions

The calculations of greenhouse gas (GHG) emissions for the three scenarios rely mainly on a tool developed by Environment Canada: the GHG Calculator for Waste Management. This tool has been designed specifically for the field of waste management, in order to assess different scenarios regarding their GHG emissions. This tool has been based on the waste reduction model (WARM) developed by the US EPA (United States Environmental Protection Agency) and has been adapted to the Canadian context. It is intended for municipalities and other waste management actors that would like to evaluate the potential for GHG reduction under different waste management practices. It must be noted that the GHG Calculator provides only estimations and should not be used for a detailed inventory of GHG. However, the estimations can serve as a basis for comparison of different scenarios.

Table 3: GHG emissions and sinks from the three waste management strategies considered. (Adapted from US EPA, 2006)

Biowaste management strategy	GHG emissions and sinks		
	Upstream	During operation	Downstream
Landfilling	***Emissions*** - Collection of waste - Transport to landfill	***Emissions*** - Landfill machinery	***Emissions*** - Landfill methane ***Offsets*** - Carbon storage in landfill
Home-composting		***Emissions*** - Methane and Nitrous oxide	***Offsets*** - Soil carbon storage
Large-scale composting	***Emissions*** - Separate collection of waste - Transport to composting facility	***Emissions*** - Composting machinery - Methane and Nitrous oxide	***Offsets*** - Soil carbon storage

The GHG calculator considers a reference scenario and an alternative scenario with similar waste amounts and composition to deal with and estimates emissions associated with both scenarios. In this study, a reference scenario and two alternative scenarios are considered: Scenario A - Home-composting and Scenario B - Large-scale composting.

GHG emissions are evaluated from a life cycle perspective: upstream emissions, emissions during operation and downstream emissions for each strategy (Table 3).

3.3.1. *Landfilling*

Landfilling organic waste generates carbon dioxide (CO_2) emissions from collection and transportation trucks, as well as from machinery used at the landfill. ICF Consulting for Environment Canada (2005) estimates GHG emissions from landfill machinery to amount around **5 kg CO_2-eq.ton^{-1} ww** (wet waste). Collection and transportation associated emissions are in the range of 1-20 kg CO_2-eq.ton^{-1} ww, according to Environment Canada (ICF Consulting, 2005). For collection and transport to a landfill located 150 km away, Eisted *et al.* (2009) reported CO_2 emissions of 24-44 kg CO_2-eq.ton^{-1} ww. Of course, this value highly depends on the geographical characteristics of the municipality, i.e. the density and the distance to the landfill. An average value of **20 kg CO_2-eq.ton^{-1} ww** was used in this study.

When organic waste is buried in the ground, it starts to decompose under anaerobic conditions and produces landfill gases (US EPA, 2006). Landfill gases contain mainly methane that can escape to the atmosphere and act as a potent GHG. Indeed, methane has a global warming potential 25 times higher than carbon dioxide which is the reference (IPCC, 2007). In the past, open dumps and landfills let methane freely escape. Today, most landfills have a landfill gas recovery system. ICF Consulting (2005) reports a recovery rate of 75% and assumes that 10% of methane is oxidised into carbon dioxide. The recovered methane is then flared into CO_2. This carbon dioxide is not included in our inventory because of its biogenic origin. Some landfills might use the methane recovered in order to produce electricity and doing so avoid emissions by replacing the burning of fossil fuel. However, few landfills are equipped to produce electricity in Québec, so this aspect has not been considered. As methane emits continuously from a landfill, even when the landfill has been closed, a time-scale of 100 years has been used in the GHG emission calculations (ICF Consulting, 2005). Finally, ICF Consulting estimates methane emissions to be **300 kg CO_2-eq.ton^{-1} ww** for food waste and **140 kg CO_2-eq.ton^{-1} ww** for garden waste.

The last emissions associated with landfilling are actually an offset and relate to carbon matter stored in the landfill. Indeed, food and garden waste are not completely decomposed by bacteria and some of the carbon remains stored in the landfill (US EPA, 2006). A landfill constitutes a carbon sink because it stores carbon that would naturally be released into the atmosphere. ICF Consulting (2005) estimates those negative emissions around **-90 kg CO_2-eq.ton^{-1} ww** for food waste and **-590 kg CO_2-eq.ton^{-1} ww** for garden waste. The difference between food and garden waste stem from their different composition which determines how well bacteria can decompose it.

Table 4 summarises emission factors associated with landfilling.

Table 4: Emission factors associated with landfilling.

	Landfilling (ton $C0_2$-eq/ton ww)				
	Collection and transport to landfill	Landfill machinery	CH_4 emissions	Carbon sequestration in the landfill	**Net emissions**
Food waste	0.02	0.005	0.30	-0.09	**0.24**
Garden waste	0.02	0.005	0.14	-0.59	**-0.43**

3.3.2. *Home-composting*

Home-composting, as on-site treatment of organic waste, does not have any emissions associated with collection and transport of waste. However, during the composting process, small quantities of methane (CH_4) and nitrous oxide (N_2O) are produced (Amlinger *et al.*, 2008; Andersen *et al.*, 2010; Martinez-Blanco *et al.*, 2010). Since methane and nitrous oxide have high global warming potentials, respectively 25 and 298 that of similar amount of carbon dioxide (IPCC, 2007), it is important to take these emissions into consideration. Amlinger *et al.* (2008) reported emissions of 76 and 186 kg CO_2-eq.ton^{-1} ww. Andersen *et al.* (2010) measured emissions of 100-239 kg CO_2-eq.ton^{-1} ww, while Martinez-Blanco *et al.* (2010) recorded a value of 204 kg CO_2-eq.ton^{-1} ww. A low average of **100 kg CO_2-eq.ton^{-1} ww** was used, assuming that the composting process was well-managed.

Home-composting produces a humus-like end material that can be used as a soil amendment. In the same manner than landfill can sequester some carbon, compost also acts as a carbon sink, as explained by US EPA (2006). Indeed, only 80% of organic matter is emitted as CO_2, while the 20% left remains stored in the compost and resistant to further decay (US EPA, 2006). The mechanisms are still under research at the US EPA; however, US EPA has already proposed a negative emission of **-270 kg CO_2-eq.ton^{-1} ww** (US EPA, 2006). This value is valid for both food and garden waste because compost is made of an equal proportion of both.

Table 5 summarises emission factors associated with home-composting.

3.3.3. *Large-scale composting*

Introducing a separate collection for organic waste generates additional CO_2 emissions from collection trucks. ICF Consulting (2005) considers in its GHG Calculator that emissions from biowaste collection are similar to those from garbage collection. However, since less waste is collected per household in an organic waste collection system compared to conventional collection, associated emissions per ton must be higher.

Table 5: Emission factors associated with home-composting.

	Home-composting (ton $C0_2$-eq/ton ww)		
	CH_4 and N_2O emissions	Carbon sequestration in soil	**Net emissions**
Food waste	0.1	-0.27	**-0.17**
Garden waste	0.1	-0.27	**-0.17**

Table 6: Emission factors associated with large-scale composting.

	Large-scale composting (ton $C0_2$-eq/ton ww)				
	Separate collection and transport to composting plant	Composting machinery	CH_4 and N_2O emissions	Carbon sequestration in soil	**Net emissions**
Food waste	0.028	0.018	0.06	-0.27	**-0.16**
Garden waste	0.028	0.018	0.06	-0.27	**-0.16**

Adhikari *et al.* (2010) assume that transport for organic waste emits 33% more CO_2 than transport for garbage. US EPA (2006) estimates emissions from biowaste transportation around 28 kg CO_2-eq.ton^{-1} ww, compared to 20 kg CO_2-eq.ton^{-1} ww for garbage. The figure of **28 kg CO_2-eq.ton^{-1} ww** has been used. ICF Consulting estimates emissions from composting machinery at **18 kg CO_2-eq.ton^{-1} ww**.

A source of GHG emission that has not been taken into account in the GHG Calculator from Environment Canada is emissions occurring during the composting process. Indeed, those emissions have not been researched by the US EPA and thus have been considered as negligible. However, it was shown, like for home-composting, that methane (CH_4) and nitrous oxide (N_2O) are emitted during large-scale composting (Amlinger *et al.*, 2008). Amlinger *et al.* reports emissions between 20 and 80 kg CO_2-eq.ton^{-1} ww for windrow composting depending on feedstock. Besides, the 2006 IPCC Guidelines for National Greenhouse Gas Inventories suggests a value for CH_4 and N_2O emissions during composting (IPCC, 2006), respectively 4 kg CH_4.ton^{-1} ww and 0,3 kg N_20.ton^{-1} ww, adding up to 189 kg CO_2-eq.ton^{-1} ww. Therefore, CH_4 and N_2O emissions have been added to the GHG Calculator. An average value of the different studies has been used, that is to say **60 kg CO_2-eq. ton^{-1} ww**.

As well as for home-composting, large-scale composting produces mature compost that helps holding carbon matter in the soil and thus acts as a carbon sink. The negative emissions from carbon sequestration in soil have been calculated at **-270 kg CO_2-eq.ton^{-1} ww** (US EPA, 2006).

Table 6 summarises emission factors associated with large-scale composting.

3.4. Other environmental impacts: traffic, noise, landfill burden, compost quality

Impacts of the frequency of collection on traffic and noise in the three scenarios are only qualitatively assessed in comparison to the reference scenario.

The burden on landfill sites refers to the amount of waste landfilled, and so is quantitatively evaluated thanks to the annual quantity of organic waste landfilled in the three scenarios. The burden on landfill is also related to the amount of land required for landfilling (Adhikari *et al.*, 2010).

The compost quality is only assessed for scenarios A and B, based on case studies and literature review (Colon *et al.*, 2010; Papadopoulos *et al.*, 2009; Smith and Jasim, 2009; Füleky and Benedek, 2010), as well as national guidelines (Composting Council of Canada; Canadian Council of Ministers of the Environment).

3.5. Performance against government targets

The provincial government of Québec has set a target of 60% recovery for the organic fraction of municipal solid waste in its *Action Plan 2011-2015* (MDDEP, 2011).

The performance of the three scenarios with regards to government targets will be assessed according to their capture rate, i.e. the amount of organic waste captured by composting as a proportion of the total organic waste. This proportion is then compared to the 60% target.

4. RESULTS

This section presents the results obtained from applying the methodology. These results are then discussed in the discussion chapter.

4.1. Scenarios

Given that the annual production rate of organic waste in Québec is 184 kg/pers (Recyc-Québec, 2009) for a city of 50 000 inhabitants, the case study has to deal with 9200 tons of annual organic waste, of which 6348 tons are food waste and 2852 tons are garden waste.

The scenarios designed in the methodology are applied to our case study (Table 7). An example of calculation is presented in Appendix I.

In Reference Scenario, the entire organic waste load is landfilled, i.e. 9200 tons. In Scenario A and B, the quantity of waste landfilled is lower, respectively 5949 tons and 3744 tons, that is a decrease of 39% and 59%. The waste diverted from landfilling is entirely treated by large-scale composting in Scenario B and by a combination of home-composting and large-scale composting in Scenario A.

4.2. Economic impacts

The following section calculates annual costs associated with the three scenarios for our case study, a city of 50 000 inhabitants (Table 8).

In Reference Scenario, the cost for landfilling organic waste is $1 334 000 every year for a city of 50 000 inhabitants. Compared to Reference Scenario, Scenario A will cut costs by 15% ($1 135 993), while Scenario B will increase costs by 4% ($1 388 556).

Table 7: Waste quantities handled by each strategy in the three scenarios (expressed in tons). *Detailed calculations are presented in Appendix I.*

	Reference Scenario		Scenario A - Home-Composting		Scenario B - Large-scale composting	
	Food waste	Garden waste	Food waste	Garden waste	Food waste	Garden waste
Landfilling	6348.0	2852.0	5078.4	570.4	3174.0	570.4
Home-Composting	-	-	1269.6	570.4	-	-
Large-scale composting	-	-	-	1711.2	3174.0	2281.6
Subtotal	6348.0	2852.0	6348.0	2852.0	6348.0	2852.0
Total	9200.0		9200.0		9200.0	

Table 8: Costs of the three scenarios (expressed in CAD ($)). *Detailed calculations are presented in Appendix I.*

	Reference Scenario		Scenario A - Home-Composting		Scenario B - Large-scale composting	
	Food waste	Garden waste	Food waste	Garden waste	Food waste	Garden waste
Landfilling	$920 460	$413 540	$690 345	$88 412	$460 230	$82 708
Home-Composting	-	-	$63 480	$28 520	-	-
Large-scale composting	-	-	-	$265 236	$491 970	$353 648
Subtotal	$920 460	$413 540	$753 825	$382 168	$952 200	$436 356
Total	$1 334 000		$1 135 993		$1 388 556	

The cost for landfilling is much lower in both Scenario A and B than in Reference Scenario, $778 757 and $542 938 compared to $1 334 000, respectively. However, additional costs arise from the diversion of organic waste via composting, especially from separate collection and large-scale composting.

Scenario B is the most expensive, while Scenario A is the least expensive and the reference scenario comes in the middle. Scenario A being the least expensive is also valid when food waste and garden waste are considered separately (Fig. 2). There is no difference in terms of costs between handling food or garden waste.

4.3. Greenhouse gas emissions

This section presents annual GHG emissions associated with the three scenarios (Table 9).

In Reference Scenario, 280 tons CO_2-eq are emitted every year by collection, transport and landfilling of organic waste in a city of 50 000 inhabitants. In comparison, Scenario A, which has an emphasis on home-composting, will emit 283 tons CO_2-eq, an increase of 1% of GHG emissions. Scenario B, with separate collection and composting, will save emissions of 391 tons CO_2-eq, and thus decrease emissions by 240% compared to Reference Scenario.

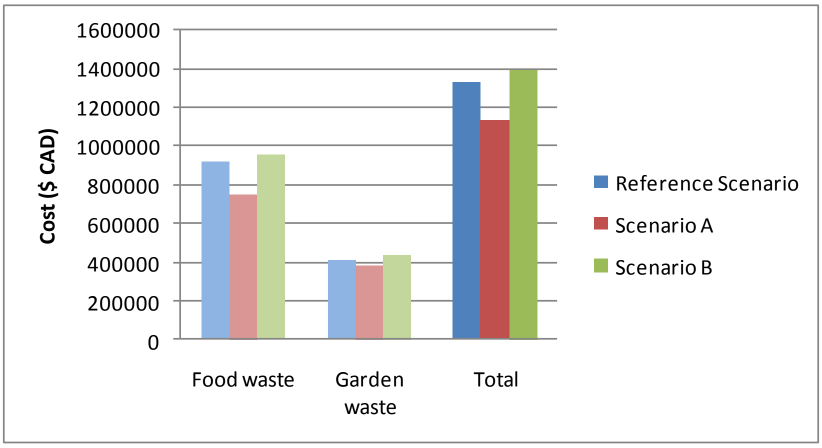

Figure 2: Comparison of the scenarios costs (expressed in CAD) according to the type of waste.

Table 9: GHG emissions of the three scenarios (expressed in tons CO_2-equivalent). *Detailed calculations are presented in Appendix I.*

	Reference Scenario		Scenario A - Home-Composting		Scenario B - Large-scale composting	
	Food waste	Garden waste	Food waste	Garden waste	Food waste	Garden waste
Landfilling	1491.8	-1212.1	1118.8	-242.4	745.9	-242.4
Home-Composting	-	-	-215.8	-97.0	-	-
Large-scale composting	-	-	-	-280.6	-520.5	-374.2
Subtotal	1491.8	-1212.1	903.0	-620.0	225.4	-616.6
Total	279.7		283.0		-391.2	

Emissions associated with landfilling are smaller in Reference Scenario than in Scenario A and B, respectively 280 tons CO_2-eq in Reference Scenario, 876 tons CO_2-eq in Scenario A and 504 tons CO_2-eq in Scenario B. However, negative emissions from home-composting and large-scale composting contribute to lower the total emissions of Scenario A and B.

Scenarios A and B do reduce emissions compared to Reference Scenario when food waste only is considered (Fig. 3). However, if garden waste only is considered, Scenarios A and B save emissions but not as much as Reference Scenario does. GHG emissions depend largely on the type of waste handled (food or garden waste).

4.4. Other environmental impacts

4.4.1. *Traffic and noise*

In Reference Scenario, all organic waste is collected with garbage, therefore a weekly garbage collection is in place, as it is the case in almost all cities in Québec (Chamard, unpublished data).

In Scenario A, only a share of people are involved in home-composting; people who do not practice home-composting still need a weekly collection for ordinary garbage. In practice, weekly garbage collection is maintained even though the waste load is lowered by home-composting

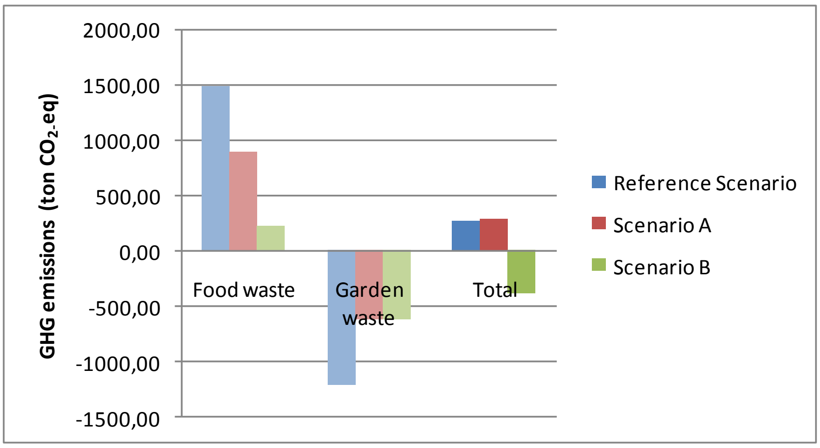

Figure 3: Comparison of the scenarios GHG emissions (expressed in tons CO_2-eq) according to the type of waste.

(Chamard, unpublished data). Therefore, traffic and noise due to trucks collecting ordinary garbage remain at the same level compared to the reference scenario. Additionally, seasonal garden waste collections can increase traffic and noise by 4 to 15%, which corresponds to 2 to 8 additional collections every year.

In Scenario B, additional collection for biodegradable waste is set up, usually taking place once a week. In compensation, garbage collection frequency is reduced to once every fortnight because of the lower waste load. Overall, waste is collected 1,5 times per week, an increase of 50% compared to the reference scenario. Consequently, the traffic and noise caused by waste collection in the city will increase and induce more disturbances for citizens.

4.4.2. ***Burden on landfill***

In Reference Scenario, 9200 tons of organic waste are landfilled every year. Since landfilling requires 33 ha of tillable land per million tons of waste (Adhikari *et al.*, 2010), Reference Scenario will require an additional 0,30 ha of land dedicated to landfilling every year.

In Scenario A, 3551 tons of organic waste are diverted from landfills and composted instead. Only 5649 tons end up in a landfill annually. In term of land use, it would require 0,19 ha every year, which makes a reduction of 39% compared to Reference Scenario.

In Scenario B, 5456 tons of organic waste are composted, while only 3744 tons are landfilled. In term of land use, Scenario B would use 0,12 ha for landfilling purpose every year. This represents a decrease of 59% compared to Reference Scenario.

4.4.3. ***Compost quality***

In general, the quality of the end-product depends on the quality of the inputs.

In Scenario A, the users have full control over the entire home-composting process. As they will use the end-product, they pay attention to the quality of source-sorted organics they put in the composter. As exemplified by pilot projects, the quality of compost produced at home can be an issue at the beginning of the project, due to inadequate C/N ratio for instance, but a few adjustments enable to reach high quality compost (Papadopoulos *et al.*, 2009). Besides, people involved in home-composting are often more sensitive to environmental issues, which results in higher quality sorting.

In Scenario B, a centralised organic collection system along with large-scale composting enables the production of compost at a larger scale. However, as people are not aware of the full composting process, they might be less cautious with sorting organic waste and not do it properly. Besides, a separate collection is intended not only to those environmentally-aware, but to all of the inhabitants of the city. Furthermore, as pointed out by Solinov (2006), the higher the number of accepted material in the separate collection, the greater the amount of impurities. Indeed, if soiled paper and cardboard are allowed in the separate collection, it might be very tempting to throw non-compostable cutlery together with paper plates. So the quality of inputs is often lower in a separate collection than in home-composting. Nevertheless, large-scale composting plants have the advantage to use advanced technology such as automatic or manual pre-sorting, prior to composting, which helps removing impurities. Besides, as the end-product is to be sold, it has to be tested and classified according to industry standards, meaning that a certain quality of the end-product has to be met. National guidelines restrict the production and sale of compost (CCME, 2005).

4.5. Performance against government targets

The *Québec Policy on Waste Management* requires an organic waste recovery rate of 60%. In our case study, it means that, out of 9200 tons of organic waste generated, 5520 tons should be diverted from landfilling and treated in an appropriate manner.

Reference Scenario – Landfilling

By definition, in this scenario all organic waste is landfilled so the recovery rate is 0%.

Scenario A – Home-Composting

In this scenario, 1840 tons of food and garden waste are recovered through home-composting, 1711 tons of garden waste are turned into compost at a centralised composting facility. Therefore, the recovery rate is 39%.

Scenario B – Large-scale Composting

The separate collection enables to divert and turn into compost 5456 tons of food and garden waste, reaching a recovery rate of 59%.

5. DISCUSSION

This chapter examines the meaning and the implications of the results. A comparison with results from the literature is also carried out, as well as a discussion on uncertainties.

5.1. Scenarios

Three scenarios have been designed and applied to a case study: a city of 50 000 inhabitants in the province of Québec, Canada. Those scenarios are based on waste production rates in Québec and therefore cannot be transferred directly to other countries. Indeed, the amount and composition of waste varies among countries, especially between northern and southern countries. In Québec, a person generates 184 kg of organic waste per year, similarly to a person in Denmark who generates 136-183 kg per year (Andersen *et al.*, 2010), while other studies record an annual organic waste production of 235 kg in Spain and 330 kg in Greece (Colon *et al.*, 2010; Papadopoulos *et al.*, 2009). If the study is to be applied in another region, the scenarios should be carefully adapted to the country's context and specific data are needed.

During the design of the scenarios, percentages were chosen to reflect the potential capture rates resulting from the implementation of home-composting or separate biodegradable waste collection. In Scenario A – Home-composting, the capture rate by home-composting was set to 20%. However, the actual rate depends on many factors and especially on the geographic situation of the city under study: a densely populated urban area such as Montréal and its suburbs is likely to have a lower home-composting percentage than a rural area where most houses have a garden. Besides, participation rates may be higher during the study because participants are motivated by the study. When considering the potential for home-composting in Canada, Adhikari *et al.* (2010) built a scenario with 60% of organic waste treated by home-composting. Although this scenario yielded very good economic and environmental benefits, it seems to be very optimistic and not feasible in practice. That is why a capture rate of 20% was chosen in the present study.

In Scenario B – Large-scale composting, 80% of garden waste and 50% of food waste were assumed to be captured by separate collection.

Again, even though literature reported such rates, it might overestimate the capture rate found in reality because the population under study is likely to be more motivated than the average population. Although literature about overall capture rates is available (Recyc-Québec, 2009b), very few studies distinguish food waste and garden waste. According to Mr Chamard (Chamard J.L., Chamard et Associés, personal communication), the amount of food waste disposed of in separate collection is very low, and could even drop to 25% of total food waste. Separating food waste at the source is often considered more constraining than doing so with garden waste: food waste must be kept in a separate container in the kitchen, and then transferred to the bin outside. It is often associated with dirt, unpleasant odors and extra work. Therefore, since the impacts are not the same with a capture rate of 25 or 50%, it would be interesting to run the model for different capture rates. Then, when it is applied to a case study, the potential capture rate should be investigated and the study could be done on a case-by-case basis, in order to take into consideration local conditions.

5.2. Economic impacts

Scenario A: Home-composting

Implementing Scenario A in a municipality would cut costs of organic waste management by 15%. This is due to the fact that costs for home-composting are much lower than landfilling costs. Results are in line with those from Adhikari *et al.* (2010) who reported similar costs for home-composting (41 $/ton compared to 50 $/ton estimated in this study).

Scenario A also contains a separate collection system for garden waste which is slightly more costly than collecting it with garbage. The choice to implement a seasonal collection for garden waste is often not dictated by economics but rather by a will to increase recovery rate and produce compost.

Dealing with organic waste at home enables to reduce collection costs as well as treatment costs. The provincial tax on landfilling was raised from 10 $/ton to 20 $/ton in 2011 and is likely to increase even more in the future (MDDEP, 2011). Therefore home-composting will be even more economical in the future. As savings reach 15% when 20% of organic waste is diverted by home-composting, it would be very interesting for a municipality to encourage even more home-composting and reach a higher participation rate. However, because of waste restrictions in home-composting and of a limited number of people with access to a garden, the diversion rate for organic waste will reach a certain ceiling and so will the municipal savings.

Scenario B: Large-scale composting

Conversely, implementation of Scenario B would increase costs by 4% in comparison to landfilling. This is due to higher costs for separate organics collection than for conventional garbage collection. Treatment cost for landfilling and composting are similar and even slightly lower for composting (65 $ and 63 $/ton respectively). It can be noted that thanks to the raise of provincial landfill tax, composting is now competitive with landfilling. If provincial landfill tax is to be raised again, composting organics in a large-scale composting facility could become much more economical than landfilling. It must be kept in mind that costs for communication and awareness campaigns were not considered in Scenario B. It was not possible to estimate those costs so they were not included. However, communication and awareness campaigns are essential to achieve high participation rates. Adding those costs would make Scenario B more expensive, especially in the first years when communication is most needed.

As a comparison, Adhikari *et al.* (2010) consider higher costs for their landfilling and large-scale composting scenarios. In this study, landfilling (including collection) is estimated to cost around 145 $/ton and composting (including collection) 155 $/ton while Adhikari *et al.* assume 165 $/ton for landfilling and 241 $/ton for composting. These differences may be explained by the fact that their study encompasses both Canada and Europe and thus averaged costs from both regions. This is a commonly held view that collecting separately organic waste is much more expensive than mixing it with garbage and Adhikari *et al.* assume that it costs 33% more for collection only. It is understandable that a separate organic waste collection costs more than a garbage collection. There is effectively less waste to collect while the transport costs remain the same. However, the study I conducted at Chamard et Associés (Chamard et Associés, unpublished data) shows that the difference is not so great in practice. Indeed, the average collection costs are 80 $/ton for garbage and 92 $/ton for organic waste. It only represents an increase of 15%. An explanation could be that composting facilities are located closer to the city than landfill sites and thus transport costs are reduced. Our results are in line with the study by Blackburn Lefebvre (2010) which reports costs of 120 $/ton for organic waste collection and 70 $/ton for composting in the city of Sherbrooke in Québec.

When analyzing composting costs, we should keep in mind that only a few municipalities in Québec have implemented a separate collection system for biodegradable waste. Therefore, the availability of data on which to base the average costs is limited. Besides, although some waste management companies establish a price per ton, most of them offer a price per door, i.e. a price per house or flat. In this case, the cost per ton depends on the amount of organic waste disposed of in the separate collection. Whether a household puts 1 kg or 10 kg of organic waste in the separate collection, the price per household will remain constant but the cost per ton will vary greatly. However, it was decided to keep a cost per ton because the scenarios are designed according to waste quantities, and it makes the results easier to compare to other studies which also use costs per ton (Adhikari *et al.*, 2010; Blackburn Lefebvre, 2010; Diagne, 2009). Finally, a city which would like to know how much a separate collection would cost should either ask local companies for prices per ton or adapt the methodology to prices per door.

The present results suggest that implementing Scenario B would require only a small additional investment from a municipality. However, this municipality will have to consider additional costs related to extended communication campaigns. It was expected that Scenario B would be more expensive than the reference scenario because it involves additional collection and composting is not seen as a competitive option compared to landfilling. Some municipalities as well as citizens are reluctant to implement a separate biodegradable waste collection because they think it would drive municipal taxes up. Surprisingly, the increase in costs is relatively low and in turn could convince more easily of the benefits from using separate collection for biodegradable waste.

5.3. Greenhouse gas emissions

Scenario A: Home-composting

The results show that, in terms of GHG emissions, it has almost no impact to replace Reference Scenario with Scenario A. Indeed, it would increase emissions by 1%. This result might be surprising as it would be expected that replacing landfilling by home-composting reduces both emissions from collection and landfilling. First, it can partially be explained by the low capture rate for home-composting in Scenario A: only 20% of organic waste is diverted from landfill. If this rate was higher, the performance of Scenario A, in terms of GHG emissions, would be better. For that purpose, a sensitivity analysis was done: Instead of using a capture rate of 20% of organic waste by home-composting as assumed in Scenario A, the capture rate was raised to 50% in order to evaluate the importance of the participation. The calculations were done as explained in the methodology and they show that a hypothetical capture rate of 50% of organic waste by home-composting would lead to a reduction of 223% in GHG emissions. However, at the city' scale, a rate of 50% may not be achievable in practice.

Another point of interest comes from the methodology. If we look at figure X, emissions are indeed lower for Scenario A than for Reference Scenario with regards to **food waste**. However, for **garden waste**, avoided emissions are greater in Reference Scenario than in Scenario A. These differences can be explained by emission factors used in the methodology:

Landfilling one ton of food waste emits 0,24 ton CO_2-eq, while home-composting it emits -0,17 ton CO_2-eq. On the other hand, one ton of garden waste emits -0,43 ton CO_2-eq when landfilled while it emits -0,17 when home-composted. Landfill acts as a powerful carbon sink for garden waste and this is the reason why home-composting does not cut emissions compared to landfilling. Landfill is a carbon sink because it stores carbon that was buried into the ground and did not decompose under anaerobic conditions, especially woody waste (Lou and Nair, 2009). However, taking or not into account carbon storage in landfill is under debate. In this thesis, it was decided to count landfill carbon storage in the calculations as it was done by the US EPA (US EPA, 2006) and Environment Canada (ICF Consulting, 2005). Carbon storage in landfill is an anthropogenic sink and should be counted in overall emissions because stored carbon would otherwise degrade to CO_2 in the atmosphere. Other studies do not take into consideration carbon storage in landfill and in this case, landfill is not a carbon sink anymore and emissions associated with landfilling are much higher (Adhikari *et al.*, 2010).

Finally, it can be inferred from the results that home-composting is a preferable option for treating food waste while landfilling remains a competitive option for treating garden waste with respect to home-composting or centralised composting due to its high carbon storage potential. Landfilling would perform even better if it was coupled with waste-to-energy technology (producing energy from landfill gas) (Lou and Nair, 2009). Moreover, the participation rate is of high importance and the only way for home-composting to achieve high environmental performance is to reach high participation rates. This is however unfortunately limited by geographical and behavioral constraints.

Scenario B: Large-scale composting

Choosing Scenario B would result in a reduction of 240% of GHG emissions. Scenario B would save emissions while Reference Scenario and Scenario A emit both GHG. In this respect, Scenario B is the most efficient scenario. Its high performance stems from the negative emissions associated with large-scale composting and above all, from the high organics capture rate. Indeed, as specified in the methodology, 80% of garden waste and 50% of food waste are diverted from landfilling to composting. If, as discussed earlier, the capture rate of food waste dropped to 25% instead of 50%, Scenario B would only lead to GHG reduction of 13%. Therefore, the capture rate, and correspondingly the participation rate of the population are significant parameters for calculating environmental performance.

It is worth noting that, even with an additional collection, Scenario B still has the lowest impact on climate change. Emissions from collection and transport are small compared to emissions of CH_4 and N_2O from composting (respectively 0,028 and 0,06 ton CO_2-eq/ton ww) and very small compared to negative emissions from carbon sequestration in the soil (-0,27 ton CO_2-eq/ton ww). Therefore, collection and transport of waste contribute only little to overall emissions.

It was decided to consider an emission factor of -0,27 ton CO_2-eq/ton ww for carbon sequestration in the soil resulting from compost application, as justified by Environment Canada (ICF Consulting, 2005). However, as discussed in the literature review, this factor depends largely on the final use of the compost (Boldrin *et al.*, 2009). If the compost were landfilled instead of being spread on agricultural soil, the emissions avoided would not be so large: compost spread on agricultural land acts as a growth media for plants which store carbon dioxide.

As a comparison, Adhikari *et al.* (2010) found that their scenario with emphasis on large-scale composting increased emissions by 7% compared to the landfilling scenario. This conclusion is different from the ones made in this study. However, the different conclusions can be seen as the result of having different hypotheses. In their scenario, 80% of organic waste is composted while 20% is landfilled. The authors assumed that, because of the increasing amount of organic waste treated via composting, there was not enough organic waste landfilled for methane capture to be economical. Therefore, methane capture was not considered for the 20% of waste landfilled, while it was considered in the reference scenario (100% of organic waste landfilled). Besides, the final use of the compost, and thus the negative emissions associated, were not considered in their study. This is why GHG emissions from the large-scale composting scenario were higher than in the landfilling scenario in Adhikari *et al.*'s study. The non CH_4-capture hypothesis was not used in the present study because methane capture is a very efficient way to reduce GHG emissions and we assumed that it won't be abandoned in the future.

5.4. Other environmental impacts

5.4.1. *Traffic and noise*

As presented in the Results, Scenario B increases the amount of collection by 50% which will generate additional traffic and noise from collection trucks. This is definitely a major problem, especially in densely populated areas where noise is already coming from other sources and traffic is a growing problem. These additional constraints resulting from the biodegradable waste collection are likely to arouse reluctance among the participants. Another issue associated with a third collection system (in addition to garbage and recyclable materials) is the installation of a new bin. Indeed, many houses do not have room for three different bins, especially in cities like Montréal where multi-storey houses prevail.

Finally, while Reference Scenario and Scenario A almost keep things how they are, Scenario B is likely to raise logistical problems and public reactions that should be taken into consideration. If Scenario B is to be chosen, there would be a need for public consultation in order to increase general acceptance of the proposed changes.

5.4.2. ***Burden on landfill***

Among the three scenarios, Reference Scenario puts the highest burden on landfill with an additional 0,30 ha of land required every year for landfilling. This scenario is likely to raise problems in Québec where many landfills have reached their maximal capacity earlier than planned and where the opening of new landfills is made difficult by the NIMBY (Not In My Back Yard) syndrome (Blackburn Lefebvre, 2010; Stypka *et al.*, 2005).

Scenario B, and to a lesser extent Scenario A, would greatly decrease the burden on landfills with only 0,12 and 0,19 ha of land required every year, respectively, compared to 0,30 ha. They would increase the operational life cycle of landfills and help reduce the pollution associated with landfills. Indeed, landfilling less organic waste would reduce leachate produced in the landfill and also decrease organic load in leachate, making it easier to treat (Papadopoulos *et al.*, 2009).

5.4.3. ***Compost quality***

Both Scenario A and B produce compost, a product with added value that can be used as soil improver or fertilizer in agriculture or landscaping. Composts from the two scenarios are generally of good quality. However, Scenario B has the advantage to produce a compost that can be sold and thus yield some profit: from 10 $ to 90 $/ton of compost, depending on the quality and the packaging (Diagne, 2009). Moreover, this compost may be used on agricultural or depleted soils and thus play an ecological role. Scenario A produces compost that has no economic value but avoids costs associated with the purchase of industrial compost for the citizen involved in home-composting. The use of compost from home-composting is nevertheless difficult to track down and analyze.

5.5. Performance against government targets

As shown in the results, Reference Scenario is the worst-case scenario when it comes to meeting government targets. Indeed, while the government of Québec requires 60% of organic waste to be recovered, this scenario has a diversion rate of 0% because all the organic waste is landfilled. This scenario does not comply at all with environmental guidelines established by the government of Québec. If the government was to introduce penalties depending on the organic waste recovery rate, the municipality which chose this scenario would be in a bad position and it would take some time before they can meet the required target.

Scenario A does better than Reference Scenario with a recovery rate of 39% of organic waste, but still does not reach the 60% target set by the government. A way to improve the recovery rate would be to increase the participation in home-composting by educational or financial means as discussed later. It seems however very difficult to reach the 60% target by only relying on home-composting. The participation rate in home-composting is limited by considerations of space availability and restrictions on types of waste accepted in the compost.

Finally, Scenario B almost reaches the 60% target (59%) and thus complies with the government guidelines. However, this rate depends on the quantity of waste disposed of in the separate collection and thus on the willingness of people to engage in such a system. If the inhabitants do not adhere to the new system, then the recovery rate would drop under 60%. But efficient implementation of Scenario B would enable to reach even higher rates, as discussed in the recommendation section. Municipalities which engage in Scenario B would be well equipped to cope with a future ban on landfilling planned in 2020.

5.6. Summary

Scenario A – Home-composting has a lower impact than Reference Scenario on the economic aspect and on the burden on landfill, and it is closer to the compliance with the 60% target of organic waste recovery. The impact on GHG emissions as well as on traffic and noise are similar or slightly higher than those of Reference Scenario (Table 10). It must be kept in mind that Scenario A would perform much better on both economic and environmental sides if the participation rate of the population could be significantly increased.

Scenario B – Large-scale composting has a much lower impact than Reference Scenario on GHG emissions and landfill burden, and it complies with the 60% target. However, the costs and the impact on traffic and noise are both higher than in Reference Scenario (Table 10).

If the economic dimension is to be privileged then Scenario A may be a good solution though its environmental performance is not so high. Conversely, Scenario B would require small additional investments but has a very high environmental performance thanks to major GHG emissions savings. From a regulatory point of view, it complies with government recovery targets and so is on the right track to anticipate the future ban on landfilling. Therefore, the implementation of a separate biodegradable waste collection followed by large-scale composting seems to be the best way to comply with government guidelines and achieve high environmental goals.

Table 10: Summary of the impacts of Scenario A and B, expressed in percentage compared to the reference scenario. *The compost quality and the performance regarding government target are not presented because they cannot be compared to what is done in the reference scenario.*

	Impacts compared to Reference Scenario	
	Scenario A – Home-composting	Scenario B – Large-scale composting
Costs	- 15%	+ 4%
GHG emissions	+ 1%	- 240%
Traffic and noise	+ 4-15%	+ 50%
Burden on landfill	- 39%	- 59%

6. RECOMMENDATIONS

In order to optimize the performance of a separate biodegradable waste collection, it is necessary to inform and motivate the future participants to ensure the quantity and the quality of sorting. Citizen participation can be enhanced by different means: educational, economic and regulatory.

6.1. Educational tools

The social dimension is a key element in solid waste management planning and must not be neglected. The success of most solid waste management projects depends on the willingness of citizens to participate. Citizens already had to make an effort when recycling programs were implemented and they will be asked to take one step further for the implementation of the separate biodegradable waste collection. They are asked to change their habits, to devote time to learning the new system, to accept potential inconveniences and even to pay additional taxes in some cases (Stypka *et al.*, 2005). For that, they need to have the motivation and the technical means to achieve those changes.

The first step to get citizens involved in the project is to ensure that public participation is present at all stages of the planning process. Citizens should be informed of the planning of the future project and get the opportunity to give inputs and comments. Public participation can be done through the use of media, workshops, meetings, hearings. For instance, Montréal has planned to introduce a separate biodegradable waste collection all over the city by 2014. During the first step which was to choose the locations of the future organic waste treatment facilities (two composting plants and two anaerobic digestion plants), the public was informed of the potential locations via the media and invited to take part to the discussions. Then, when the project is decided, citizens should be given the possibility to bring feedbacks and comments about how it is working. Those comments should be taken into consideration and the problems encountered should be solved (Stypka *et al.*, 2005).

More specifically, training should be given to the participants in the biodegradable waste collection in order to explain what kind of waste must be put in the brown bin, the schedule of the collection and other practical information. In addition, this information should be distributed to the participants in the form of leaflets, for example. Citizens should be provided with the right tools such as a small kitchen bin to store organic waste in the house before the final disposal in the brown bin outside. Besides, a phone number can be dedicated to questions about source-sorting and composting or to report inconveniences. Finally, leaflets should be periodically sent and visits should be done to remind citizens about the importance of source-sorting organics.

A very good way to increase environmental awareness among households is to provide environmental education at school. Children can be taught about source-sorting recyclable materials and organic waste. They can visit a composting facility, and see the whole process of organic waste becoming compost. Installing a community composter at school would be a very effective way to increase children awareness and help them bring their knowledge back home, as well as share responsibilities and increase motivation at home.

Finally, redistributing compost made from organic waste collected in the area to the participants should motivate citizens because they get the opportunity to see and use a valuable product which was made from their own waste.

6.2. Economic tools

Economic instruments are efficient ways to trigger behavioural changes although they are often not easy to implement. They include incentives and tax credits, deposit-refund systems, taxes and charges (Stypka *et al.*, 2005).

A simple way to encourage composting over landfilling is to raise landfilling taxes. It was already done in 2011 when the provincial landfill taxes rose from 10 to 20 $/ton landfilled (MDDEP, 2011). The increase in taxes makes landfilling very costly and makes municipalities seriously consider alternatives such as composting. Incentives for composting and other organic treatment facilities have been launched recently (MDDEP, 2011). If those initiatives provide financial support on the technical side, they do not however guarantee the public acceptance and participation which is the key of the success in such projects.

A recent approach to reduce the amount of waste thrown in the garbage bin, based on the polluter pays principle (PPP), is the pay-as-you-throw system. First developed as the "pay-per-bag" system, it consists in charging households according to the volume of waste they generate. In this case, users are provided with special garbage bags or bins that are identified. The system has also evolved to a weight-based system to avoid compaction of waste resulting from the volume-based system. A more advanced system is then needed to record the weight during the collection: electronic chips or magnetic cards can be used. A survey in American cities which implemented one of those systems showed that the amount of waste generated was half the amount generated in other cities (Stypka *et al.*, 2005). The pay-as-you-throw system has indeed two effects: it displaces partially the waste flow from garbage to separate collections (recyclable materials or organic waste when available) and it also reduces the overall waste flow. Since citizens pay according to what they produce, they pay more attention to sorting and they avoid unnecessary waste such as excess packaging. In the case of Scenario B, it would be interesting to couple its implementation with the introduction of a pay-as-you-throw system. It would encourage people sorting organic waste instead of throwing it in the garbage bin. This kind of system is not yet developed in Québec, but the idea proved effective in the US (Seattle, Durham) and in Europe, especially Germany (Stypka *et al.*, 2005).

Another example are incentives given for investing in equipment that reduces waste ending up in landfill, for example a home-composter. As seen before, many municipalities in Québec offer a subsidy for the purchase of a home-composter. To further encourage home-composting, a community in Sweden applied a reduction fee for composting to its garbage tax, intended to people who compost at home (Eunomia, 2002).

6.3. Regulatory tools

Regulatory tools are also widely used to enforce policies as they are often easier to implement than economic tools. Authorities set targets or standards that are expected to be met under threat of penalty (Stypka *et al.*, 2005). For example, the government of Québec has set targets for organic waste recovery, i.e. 60% should be recovered in the municipal sector (MDDEP, 2011). However, this target is not coupled with a potential penalty if not met. The policy is not very restrictive so there are very few municipalities which have reached the 60% organic waste recovery target (Recyc-Québec, 2009a). A way to encourage municipalities to implement a separate collection would be to require by law the fulfillment of the target under threat of penalties.

A ban is another example of regulatory tool: the government of Québec plans to ban the landfilling of organic waste by 2020 (MDDEP, 2011). Not much information is available about the future ban, so it is unknown whether there will be penalties for polluters who do not respect this ban. As said before, the effect of the ban is likely to be weak if no penalties are planned.

Bans can be introduced at the local level too: some municipalities in Québec have banned garden waste in the garbage collection. In this case, citizens can either dispose of their garden waste via home-composting, via a seasonal garden waste collection or at a waste amenity center. This practice decreases the amount of garden waste generated by 15% on average (Recyc-Québec).

Finally, procurement provision is another tool that can be used by the government and local authorities. They could for example require the use of compost on all public land, as did the state of Maine in the US. Thus, locally produced compost would have a market and it would promote the production of compost from the organic fraction of municipal solid waste.

7. CONCLUSION AND PERSPECTIVES

This study shows that separate biodegradable waste collection followed by large-scale composting could be a good solution to improve the environmental performance of solid waste management in Québec municipalities, although it represents a slight increase in waste management costs. It is a way to recycle nutrients, produce a valuable end-product and decrease GHG emissions, instead of landfilling organic matter. However, the participation rate of the population in the creation of a separate collection system is crucial for its success. This is why economic, educational and regulatory instruments should be used in order to maximize the participation of citizens.

In this respect, the costs of educational tools used to inform and train future participants were not estimated in this study because few data were available. Investigating the costs of communication and awareness campaigns should be the focus of future studies.

Besides, this study was limited to comparing two scenarios to a reference scenario: home-composting and large-scale composting. However, anaerobic digestion is another solution for treating organic waste that is becoming more and more popular in Québec. The government of Québec already offers subsidies for building anaerobic digestion plants and such projects are currently under study in several cities in Québec. It would be interesting to study anaerobic digestion as a third alternative scenario in order to assess its potential economic and environmental benefits in Québec.

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APPENDIX I – EXAMPLE OF CALCULATIONS

The calculations of waste quantities (Table 7), costs (Table 8) and greenhouse gas emissions (Table 9) are presented here. They are detailed for Scenario A, but the same method was used for the Reference scenario and Scenario B.

<u>Waste quantities (Table 7)</u>

The total quantity of organic waste is calculated as follows:

Total organic waste (tons) = Individual organic waste production rate (tons) * Number of inhabitants

In the case study, the organic waste production rate is 184 kg per person per year (Recyc-Québec, 2009b), and the city considered has 50 000 inhabitants.

0.184 * 50000 = 9200

Therefore, the city has to deal with **9200 tons** of organic waste per year.

The food and garden waste quantities are calculated as follows:

Total food waste (t) = Percentage of food waste * Total organic waste (t)

Total garden waste (t)= Percentage of garden waste * Total organic waste (t)

In the case study, it is estimated that organic waste is made up of 69% food waste and 31% garden waste (Recyc-Québec, 2010).

9200 * 0.69 = 6348

9200 * 0.31 = 2852

Therefore, the city has to deal annually with **6348 tons** of food waste and **2852 tons** of garden waste.

The quantities of waste handled by each strategy (landfilling, home-composting and large-scale composting) are calculated as follows:

Food/garden waste landfilled (t) = Percentage of food/garden waste landfilled * Total food/garden waste (t)

Food/garden waste home-composted (t) = Percentage of food/garden waste home-composted * Total food/garden waste (t)

Food/garden waste composted at large-scale (t) = Percentage of food/garden waste composted at large-scale * Total food/garden waste (t)

In Scenario A, we assume that 80% of food waste is landfilled while 20% is home-composted (Table 1).

6348 * 0.80 = 5078.4

6348 * 0.20 = 1269.6

Therefore, **5078.4 tons** of food waste are landfilled while **1269.6 tons** of food waste are home-composted.

Similarly, it is assumed in Scenario A that 20% of garden waste is landfilled, 20% home-composted and 60% composted at large-scale (Table 1).

2852 * 0.20 = 570.4

2852 * 0.60 = 1711.2

Therefore, **570.4 tons** of garden waste are landfilled, **570.4 tons** are home-composted and **1711.2 tons** are composted at large-scale.

Costs (Table 8)

The costs are calculated with the following equations:

Cost of landfilling food/garden waste ($) = Landfilling cost per ton ($/t) * Amount of food/garden waste landfilled (t)

Cost of home-composting food/garden waste ($) = Home-composting cost per ton ($/t)* Amount of food/garden waste home-composted (t)

Cost of composting food/garden waste at large-scale ($) = Large-scale composting cost per ton ($/t)* Amount of food/garden waste composted at large-scale (t)

It was calculated that 5078.4 tons of food waste are landfilled and 1269.6 tons home-composted in Scenario A (Table 7).

We assume that landfilling costs 145.00 $ per ton, and home-composting costs 50.00 $ per ton (Table 2).

5078.4 * 145 = 690345

1269.6 * 50 = 63480

Therefore, in Scenario A, it costs **690 345 $** for landfilling food waste and **63 480 $** for composting food waste at home.

Similarly, it was calculated that 570.4 tons of garden waste are landfilled, 570.4 tons are home-composted and 1711.2 are composted at large-scale in Scenario A (Table 7).

We assume that landfilling costs 145.00 $ per ton, home-composting costs 50.00 $ per ton, and large-scale composting costs 155.00 $ per ton (Table 2).

570.4 * 145 =88412

570.4 * 50 = 28520

1711.2 * 155 = 265236

Therefore, in Scenario A, it costs **88 412 $** for landfilling garden waste, **28 520 $** for composting garden waste at home and **265 236 $** for composting garden waste at large-scale.

Greenhouse gas emissions (Table 9)

The greenhouse gas emissions are calculated with the following equations:

GHG emissions of landfilling food/garden waste (t CO_2-eq) = Emission factor for landfilling food/garden waste (t CO_2-eq/t) * Amount of food/garden waste landfilled (t)

GHG emissions of home-composting food/garden waste (t CO_2-eq) = Emission factor for home-composting food/garden waste (t CO_2-eq/t) * Amount of food/garden waste home-composted (t)

GHG emissions of composting food/garden waste at large-scale (t CO_2-eq) = Emission factor for composting food/garden waste at

large-scale (t CO_2-eq/t) * Amount of food/garden waste composted at large-scale (t)

It was calculated that 5078.4 tons of food waste are landfilled and 1269.6 tons home-composted in Scenario A (Table 7).

The emission factor for landfilling is 0.24 ton CO_2-eq per ton of food waste, and for home-composting, it is -0.17 ton CO_2-eq per ton of food waste (Table 4, 5).

5078.4 * 0.24 = 1118.8

1269.6 * –0.17 = –215.8

Therefore, in Scenario A, landfilling food waste emits **1118.8 tons CO_2-eq** while composting food waste at home emits **-215.8 tons CO_2-eq.**

Similarly, it was calculated that 570.4 tons of garden waste are landfilled, 570.4 tons are home-composted and 1711.2 are composted at large-scale in Scenario A (Table 7).

The emission factor for landfilling is -0.43 ton CO_2-eq per ton of garden waste, for home-composting, it is -0.17 ton CO_2-eq per ton of garden waste and for large-scale composting, it is -0.16 ton CO_2-eq per ton of garden waste (Table 4, 5, 6).

570.4 * –0.43 = –242.4

570.4 * –0.17 = –97.0

1711.2 * –0.16 = -280.6

Therefore, in Scenario A, landfilling garden waste emits **-242.4 tons CO_2-eq**, composting garden waste at home emits **-97.0 tons CO_2-eq** and composting garden waste at large-scale emits **-280.6 tons CO_2-eq**.