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Review

Quantification of greenhouse gas emissions from waste management processes for municipalities – A comparative review focusing on Africa

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ABSTRACT

The amount of greenhouse gases (GHG) emitted due to waste management in the cities of developing countries is predicted to rise considerably in the near future; however, these countries have a series of problems in accounting and reporting these gases. Some of these problems are related to the status quo of waste management in the developing world and some to the lack of a coherent framework for accounting and reporting of greenhouse gases from waste at municipal level. This review summarizes and compares GHG emissions from individual waste management processes which make up a municipal waste management system, with an emphasis on developing countries and, in particular, Africa. It should be seen as a first step towards developing a more holistic GHG accounting model for municipalities. The comparison between these emissions from developed and developing countries at process level, reveals that there is agreement on the magnitude of the emissions expected from each process (generation of waste, collection and transport, disposal and recycling). The highest GHG savings are achieved through recycling, and these savings would be even higher in developing countries which rely on coal for energy production (e.g. South Africa, India and China) and where non-motorized collection and transport is used. The highest emissions are due to the methane released by dumpsites and landfills, and these emissions are predicted to increase significantly, unless more of the methane is captured and either flared or used for energy generation. The clean development mechanism (CDM) projects implemented in the developing world have made some progress in this field; however, African countries lag behind.

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1. Introduction

With global warming becoming an important environmental issue, many studies have investigated the topic of greenhouse gas emissions (GHG) from waste activities (Kennedy et al., 2009; Gentil et al., 2009; Friedrich and Trois, 2010). It is estimated that the post-consumer waste sector contributes about 3–4% to the total global anthropogenic GHG emissions and for 2004–2005 this contribution amounted to 49×10^9 tonnes CO_2 e per year (Bogner et al., 2008). Although this contribution is considered relatively small, the carbon reduction opportunities for the sector are still not fully explored (ISWA, 2009), in particular in developing countries. In the year 2000, developing countries were responsible for about 29% of these emissions and this share is predicted to increase to 64% in 2030 and 76% in 2050 with landfills being the major contributor to this increase (Monni et al., 2006). A series of initiatives were highly successful and showed that large reductions in emissions are possible. For example, the contribution of the European municipal waste sector decreased from 69×10^6 tonnes CO_2 e in 1990 to 32×10^6 tonnes CO_2 e in 2007 and further reductions are projected (ISWA, 2009). The situation in developing countries is different and has to be changed if overall emissions are to be stabilized. Under the Kyoto Protocol, developing countries do not have any mandatory obligations to reduce GHG emissions; however, there are many voluntary and carbon market driven initiatives in this direction. In this context "*accurate measurements and quantification of greenhouse gas emissions is vital in order to set and monitor realistic reduction targets at all levels*" (ISWA, 2009).

In general, the majority of studies investigating the emissions of greenhouse gases from waste focused on individual waste management stages (especially waste disposal through landfilling) and other processes, in particular waste minimization and transport of waste, were not always included. Furthermore, developing countries, which due to their population sizes are important generators of municipal waste, have been less researched than their developed counterparts. As a result a more systemic and holistic approach is needed for developing countries. In this context the entire waste management system needs to be considered to properly evaluate the best strategies to reduce greenhouse gases and to assess how different waste management processes can be combined and optimized for this purpose. This is of particular importance at local level, since local authorities are in charge of managing waste on a daily basis and they are the primary agents when planning and enforcing changes. Yet for local authorities there are no clear rules and/or guidelines on how to account and report greenhouse gases from waste. Five different methodological approaches have been presented in the literature (Kennedy et al., 2009) and have been used by cities. They differ mainly by the processes of the waste management system which they include and by using different time frames for the calculation of emissions. Therefore, published GHG emissions figures from waste for municipalities cannot be compared between the different studies (sometimes for the same municipality), which make approaches towards improvement difficult to develop and assess.

The amounts of waste generated, the composition of the waste (in particular the carbon content) as well as the technologies used for handling and disposing this waste will determine the final amount of greenhouse gases emitted from a waste management system. A comparative analysis of the published literature showed that all important factors vary between developing and developed countries and they have been differently incorporated in the different accounting techniques for the waste sector (Friedrich and Trois, 2010; Couth and Trois, 2010, 2011). The aim of this paper is to summarize and compare the existing literature on the quantification of greenhouse gases from waste at municipal level in developed and developing countries with a particular focus on the African continent and South Africa. This should be the first step in the development of more holistic quantification models and overall strategies to reduce these emissions. It also aims to identify gaps and problematic areas for quantifying GHG emissions in developing countries and in particular in Africa. As such it investigates individual processes in the waste management cycle, starting with the generation and composition of waste, followed by collection and transport, disposal processes and recovery and recycling.

2. Overview of GHG quantification models for municipal waste and their relationship to the waste management processes

In an overview article, Gentil et al. (2009) described the four main types of GHG accounting methodologies in waste management as national accounting (with reference to the IPCC method), corporate level accounting (including local government, i.e. municipalities), life cycle assessment and carbon trading methodologies. At municipal level all of these four types of accounting methodologies can and have been employed in different investigations, even though the IPCC model has been designed for national use. The GHG accounting results differ greatly between these methodologies based on what was included and what was left out. To make the process of accounting and reporting more transparent, Gentil et al. (2009) propose the upstream-operating-downstream conceptual framework. In this context it is important to acknowledge that "*the choice of GHG accounting mechanism depends on the scope of the reporting, but all rely on the same basic operational data generated by the individual waste management technologies*" (Gentil et al., 2009). As a result there is a need to investigate the relationship between the accounting tools used for GHG emissions from municipalities and the actual processes/technologies which give rise to these emissions.

In general, the relationships between the quantification approach (or technique) used and the waste management processes, which make up a particular waste management system can be schematically represented as in Fig. 1. As presented in this figure there are two other important factors which shape the quantification process, namely the motives and drivers for reporting and the availability of data on the processes included in the waste management system. These factors are different in developed and developing countries, with developed countries' mandatory obligation to report greenhouse gases and therefore, the need to collect, model, calculate and/or validate data on waste management. Developing countries do not have such an obligation and their reporting process is voluntary and the availability of data is much reduced.

With regard to the application of the quantification techniques in municipalities in developing countries there are important

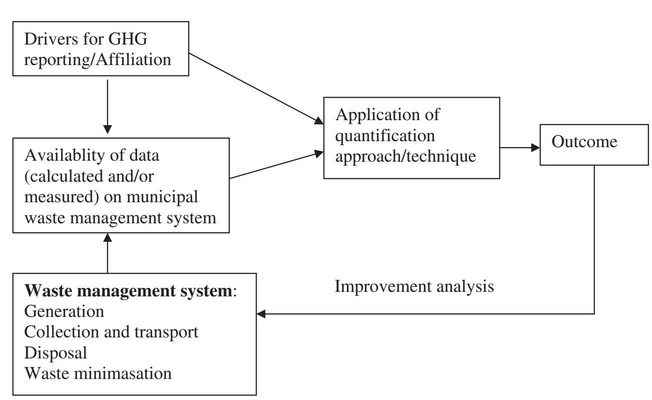

Fig. 1. General framework for greenhouse gas quantification for municipal waste.

factors influencing the outcome. These factors are related to the inherent problems developing countries are facing with regard to waste management (i.e. lack of resources, expertise, information, etc.) and they have been mentioned extensively in the literature (e.g. Henry et al., 2006; Matete and Trois, 2008; Manga et al., 2008). These factors are also affecting the availability of data and they lead to inefficient outcomes in terms of evaluation of the GHG from waste. This situation has somewhat changed with the implementation of the clean development mechanism (CDM) projects and the more rigorous calculation and validation methods they require (Couth and Trois, 2011 and Friedrich and Trois, 2010). However, by focusing only on one component/process of the waste management system (i.e. the component which earns carbon credits) better opportunities in terms of the overall outcome might be neglected. Therefore, individual processes within the waste management system have to be individually researched, but they must be seen also as parts of the system. The following sections present a more detailed review on individual processes and their determining factors in terms of GHG emissions. In this paper whenever figures are presented they refer to a mass unit of wet waste (per tonne), unless otherwise specified.

3. The generation and composition of waste and the potential for GHG emissions

The first component in any waste management system is the amount of waste generated and the nature of that waste. This is also important in terms of the quantities of greenhouse gases to be generated from that waste. Waste generation has been correlated in the literature to population size, wealth and urbanization (Bogner et al., 2008; Cointreau, 2006). The rate of increase in waste generation shows that both developing and developed countries increased their waste generation per capita, however, some countries have higher generation trends (OECD Factbook, 2009). European countries seem to have stabilized their waste generation rates and are moving towards de-coupling waste generation from economic growth (Mazzanti and Zoboli, 2008), whereas other countries, including developing countries (but also some developed countries) continue to show marked growth in the amounts of waste produced. One such country, in particular, is China (Zhang et al., 2010). In addition, a review of the absolute values showed that, due to their large populations, even if waste generation rates per capita are low, developing countries produce large amounts of waste (OECD Factbook, 2009). These amounts are expected to rise with increased urbanization and consumerism, even in cities in the developing countries that have high poverty rates. Barton et al. (2008) calculate, based on data from Shimura et al. (2001), that about 226×10^6 tonnes per year of waste will be produced by the one billion people living in the slums of the developing world. They assume an average generation rate of 0.6 kg per capita per day (or 219 kg per capita per year).

Troschinetz and Mihelcic (2009) presented a comparative analysis of the waste generation rates for 23 developing countries and the OECD (1.43 kg per capita per day), European Union (1.51 kg/capita/day) and United States (2.08 kg per capita per day). From this analysis it is evident that the majority of developing countries included have much lower generation rates, but there are also exceptions (e.g. Maldives (2.48 kg per capita per day), Thailand (1.44 kg per capita per day in urban areas like Bangkok) and Mauritius (1.30 kg per capita per day)). These exceptions are due to specific circumstances, for example the Maldives and Mauritius are island states with a large tourist industry, while waste generation in Thailand is concentrated in large cities like Bangkok. However, data summarized in Table 1 show that many other studies undertaken recently in the developing world, and especially in Africa, report much lower generation rates.

From Table 1 it can be seen that the waste generation rates per capita reported for African cities and countries are some of the lowest. This is also confirmed by Couth and Trois (2010) which took into account other published sources for generation rates. This has particular implications for GHG calculations, not only at municipal level but also at national level. In the calculations used to produce national inventories, regional waste generation rates as published by the IPCC (IPCC, 2006) are used by countries which do not have waste generation data. Most of the African countries are in this situation; although some studies which incorporated waste generation data have been published in recent years (see Table 1 – African countries). All reported rates from the literature on African case studies, as summarized in Table 1, are lower than the generation rate recommended by the IPCC (2006) methodology to be used for GHG national inventories for the African continent. It has to be underlined that municipal areas account for most of the greenhouse gases from waste of African countries and rural areas have a very low contribution (Couth and Trois, 2010). Most of the studies for the African countries included in Table 1 have been done for urban areas; therefore, the overall national generation rate for these countries could be even lower. In view of the emerging literature as presented in Table 1, the IPCC (2006) generation rate for African countries calls for revision.

Of particular interest with regard to the potential for GHG generation has been the composition of the waste and in particular the biodegradable organic fraction which will ultimately give rise to greenhouse gases. In this context it is very important to distinguish biogenic carbon, which is not included in GHG inventories because it is seen as part of the natural carbon cycle (IPCC, 2006). Table 1 also summarizes the most recently published data on the biodegradable organic fraction in developing countries and in general this fraction is much higher in these countries as compared to their developed counterparts. More details are presented by Troschinetz and Mihelcic (2009). There are also other differenced in terms of waste composition, with developing countries having on average half as much paper and cardboard, as well as glass and plastic (Troschinetz and Mihelcic, 2009). The waste compositions from African cities, and the developing world in general, tend to show high fractions in terms of organic, biodegradable materials (see Table 1 and also Couth and Trois (2010).

As cities situated in the developing world become more affluent the composition of waste is expected to change. It has been observed that with an increase in the living standards the composition of waste also changes, with the biodegradable fraction resulting from unprocessed foods decreasing and an increase in paper, plastic, glass, textile and rubber (Cointreau, 2006; Moghadam et al., 2009 and Troschinetz and Mihelcic, 2009). The consequences of this change in terms of GHG emissions depend on the disposal methods used for the waste. Barton et al. (2008) showed that if the waste composition changed towards a more developed country composition, the amount of greenhouse gases increased in both open dump and landfill without gas collection scenarios (mainly due to the increase in the paper and textile fraction). These are the most frequently used disposal methods in the developing world, including Africa.

Troschinetz and Mihelcic (2009) showed that developing countries have a higher variance in the material fraction composition of all waste categories, but in particular for the organic fraction (due to seasonal factors, affluence, domestic fuel supply, geography, etc.). This underlines the dynamic complexities in modeling waste generation in developing countries and the need for regular studies with regard to waste composition and generation. However, due to lack of resources and management capabilities, these studies are less frequent in developing countries and, in particular, in Africa.

Table 1
Recent published waste generation data for developing countries.

City/Country	Amount generated (kg/capita/day)	Biodegradable organic fraction (%)	References
Developing countries			
Allahabad – India	0.39	45.3	Sharholy et al. (2007)
Indian cities – Review	0.2–0.5	40–60	Sharholy et al. (2008)
Puducherry – India	0.59	65	Pattanaick and Reddy (2010)
IPCC rate for India[a]	*0.46*	–	IPCC (2006)
Chittagong – Bangladesh	0.25	66	Sujauddin et al. (2008)
Beijing – China	0.23	69.3	Qu et al. (2009)
Pudong (Shanghai) – China	1,11	59	Minghua et al. (2009)
Chongquing – China	1.08	59	Hui et al. (2006)
IPCC rate for China[a]	0.75		IPCC (2006)
Kuala Lumpur – Malaysia	1.5	68.6	Saeed et al. (2009)
Rasht – Iran	–	80.2	Moghadam et al. (2009)
Nablus district – Palestine	0.82	65.1	Al-Khatib et al. (2010)
Teheran – Iran	0.88	42.6	Damghani et al. (2008)
Cape Haitian – Haiti	0.21	65.5	Philippe and Culot (2009)
Lahore – Pakistan	0.84	–	Batool and Ch (2009)
Kathmandu – Nepal	0.3 (Calculated)	57.8	Alam et al. (2008)
Cambodia	0.34	66	Parizeau et al. (2006)
Chihuahua – Mexico	0.59	45	Gomez et al. (2009)
Zarqa City – Jordan	0.44	56	Mrayyan and Hamdi (2006)
Southern Sri Lanka	0.27	66	Vidanaarachchi et al. (2006)
Average developing countries	*0.58*	*59.4*	
AFRICA			
Makurdi – Nigeria	0.54	36–57	Sha'Ato et al. (2007)
Abuja – Nigeria	0.55–0.58	52–65.3	Imam et al. (2008)
Ibadan – Nigeria	0.2–0.33	–	Ayininuola and Muibi (2008)
Freetown – Sierra Leone	0.45	84	Sood (2004) in Gogra et al. (2010)
Accra – Ghana	0.4	60	Fobil et al. (2008)
Dar es Salaam – Tanzania	0.4	–	Kaseva and Mbuligwe (2005)
Botswana	0.33	68	Bolaane and Ali (2004)
South Africa developed areas less developed areas	0.8 0.3	–	Karani and Jewasikiewitz (2007)
IPCC rate for Africa (based on a study from Sudan)[a]	0.79	–	IPCC (2006)
Average African countries	*0.44*	*59.8*	

[a] Excluded from the calculations for the average.

This has particular implications for these countries and, in general, the accuracy of GHG calculations for these countries is lower.

4. Collection and transport of waste and the emission of greenhouse gases

Greenhouse gases are emitted in the collection and transport of waste from the combustion of fuel and mainly carbon dioxide, but also small amounts of other GHG (i.e. nitrous oxide and methane), are generated. Although these emissions are seldom included in GHG calculations for waste systems, it is necessary to acknowledge their contributions. In some waste management systems in developed countries (Salhofer et al., 2007) and some developing countries (Chen and Lin, 2008) they proved to be significant.

4.1. Factors important for GHG emissions in the waste collection process

There have been marked differences between the collection of waste in developed and developing countries, which in turn reflected on the GHG emissions from these processes. One of these differences is related to the collection rates of municipal waste. Collection rates have been much lower in developing countries as compared to their developed counterparts. For example OECD countries report collection rates varying between 90 and 100% in their member countries (OECD Factbook, 2009), whereby developing countries have much lower rates as some of the examples presented in Table 2 are showing. Collection rates refer to the generated waste.

Collection rates reported for African cities, except for South Africa, are much lower than those reported for other developing countries (see Table 2). These rates varied between 15% and 48% for eight sub-Saharan cities as reported by Parrot et al. (2009), with Ndjamena (Chad) displaying the lowest collection rates of 15–20% and Dar es Salaam (Tanzania) the highest (around 48%). In the developing world there have been significant differences between waste collection in rural and urban areas, with the latter generally having higher collection rates. In addition, collection rates in African countries seem to have been more variable and fluctuated in time, not only geographically, improving dramatically like in the case of Accra (Ghana) where collection rates increased from 51% in 1998 to 91% in 2000, (Fobil et al., 2008), but also deteriorating like in the recent case of Zimbabwe where economic hardship contributed to inadequate waste collection especially in low-income and informal areas (Nyathi, 2008).

In terms of GHG emissions, lower collection rates translated into lower emissions, since less transport was required and the degradation of un-collected municipal waste was assumed to be aerobic with no methane generation. Shimura et al. (2001) showed that the uncollected waste in cities in developing countries is either self-disposed (proper and improper), illegally dumped or recycled. For example, for Dar es Salaam (Tanzania) from the 1772 tonnes per day waste generated, 654 tonnes per day (36.9%) were self disposed, 847 tonnes per day (47.8%) were illegally dumped (of that 8.6% was dumped after it was collected), 130 tonnes per day (7.3%) were recycled, and only 143 tonnes per day (8.1%) were collected and disposed in a landfill site. Although the GHG emissions from this uncollected waste are expected to be lower, the other environmental impacts of municipal waste and

Table 2
Collection rates in selected developing countries/cities with emphasis on Africa.

Country/Locality	Collection rate (%)	References
South Africa – general	50	DEAT (2007)
urban kerbside	80	Karani and Jewasikiewitz (2007)
Abidjan (Côte d'Ivoire)	30–40	Parrot et al. (2009)
Dakar (Senegal)	30–40	Parrot et al. (2009)
Dar es Salaam (Tanzania)	48	Parrot et al. (2009)
Lomé (Togo)	42.1	Parrot et al. (2009)
Ndjamena (Chad)	15–20	Parrot et al. (2009)
Nairobi (Kenya)	30–45	Parrot et al. (2009)
Nouakchott (Mauritania)	20–30	Parrot et al. (2009)
Yaoundé (Cameroon)	43	Parrot et al. (2009)
China – general	79	Suocheng et al. (2001)
Indian cities	About 70	Sharholy et al. (2008) and Pattanaik and Reddy (2010)
Lahore (Pakistan)	60	Batool and Ch (2009)

its degradation products in a city environment (e.g. odours, ground water pollution, infestations, aesthetics, etc.) are relevant and have been extensively presented in the literature (e.g. Qasim and Chiang, 1994; Williams, 1998).

Developing countries are also employing different collection methods which might not be technologically advanced, but which in terms of GHG emissions have some advantages. For example, in many African cities manpower has been used in the collection of waste (e.g. for push carts, wheelbarrows, pedal tricycles, animal drawn carts, etc.) (Imam et al., 2008) which avoids the use of fossil fuels and the resultant emissions. Similar use of manpower was also reported in many other developing cities (Rouse and Ali, 2002). Although low in technology, these positive aspects in terms of GHG emissions in the collection process should be encouraged and made more efficient in existing waste management systems, since they have not only social benefits (job creation) but also environmental ones. For example, it is estimated that around 5% of the jobs of urban poor in low-income countries are due to waste collection and transport (Rouse and Ali, 2002).

4.2. Factors important for GHG emissions in the transport process

In the international literature, drawing mainly from case studies in the first world, the GHG emissions associated with the transport of waste have been emanating from life cycle assessment type of studies. These studies showed that the most important factors in the transport and collection of waste with regard to GHG emissions are:

(1) distances involved and the mode of transportation – with road transport having higher emissions per tonne of waste as compared to rail and barge transport (Salhofer et al., 2007 and Eisted et al., 2009),
(2) population density of the area from where the waste was collected and transported – with densely populated areas being the most efficient ones (Larsen et al., 2009a), and
(3) type of waste transported – with low density waste (e.g. expanded polystyrene) causing significant emissions (Salhofer et al., 2007).

For developing countries an additional factor which needs to be considered is the status quo of the vehicle fleet, which includes the age of the vehicles and their maintenance. Older vehicles and poor maintenance are associated with higher GHG emissions.

Transportation modeling studies showed that for loaded waste trucks the shortest route is not always the most fuel (and GHG emission) efficient one (Tavares et al., 2009) and road inclination and vehicle weight also played a role. There have been several recent studies investigating waste transport vehicles routing and the savings that can be achieved (Nguyen and Wilson, 2010; Arribas et al., 2010; Tavares et al., 2009, etc.). In general they showed that improvements can be achieved in terms of fuel efficiency (and associated emissions) by choosing the best routes and by changing the logistics and the organization (McLeod and Cherrett, 2008) of the waste collection and transport process. Nguyen and Wilson (2010) have calculated that for the trucks they had investigated in detail, more than 60% of the daily total fuel was consumed for the collection of waste and the transport accounts for the remaining fuel used (and associated emissions).

There have been very few studies investigating the GHG emissions from transporting waste in developing countries and the factors which are important for the developed world are only partially applicable in the developing countries. For example, population densities are seen as a factor decreasing transport emissions in first world countries (Larsen et al., 2009a and Nguyen and Wilson, 2010), however, in developing countries high population densities have been associated with un-planned informal settlements and an array of problems associated with the collection and transport of waste, e.g. the lack of access for vehicles (Fobil et al., 2008). With regard to the density of the waste, it is considered that waste densities in developing countries are higher than waste densities in developed countries and, therefore, sophisticated compactor trucks for collection and transport are not essential (Barton et al., 2008 and Imam et al., 2008) resulting in lower emissions. Low density waste fractions which have been associated with higher transport emissions make up only a small percentage of the waste in developing countries. For example, the average plastic contribution to the total waste stream for seven African studies is only 9.2% (Couth and Trois, 2010).

4.3. Quantification of GHG from collection and transport

The investigations of GHG emission from waste revealed that there is considerable variation in the amount of fuel and the resultant emissions per tonne of waste collected and transported (assumed to be wet waste). Larsen et al. (2009a) showed that for two municipalities in Denmark fuel consumption varied between 1.4 and 10.1 L diesel per tonne of waste collected and transported by road. Taking into account only GHG emissions from the collection and transport of waste a similar variability is reported in the literature. For developed countries a range of 5–50 kg of CO_2 e per tonne of wet waste was reported (Eisted et al., 2009), with European values at about 7.2 kg of CO_2 e per tonne of waste transported (Smith et al., 2001). For developing countries the GHG emissions calculated per tonne of waste were towards the lower ranges, with Chen and Lin (2008) reporting 16.38 kg of CO_2 e (or 4.47 kg C equivalents) per tonne of waste collected and transported in Taipei City (Taiwan), and Friedrich and Trois (2008) reporting 15.53 kg of CO_2 e per tonne of waste collected and transported in Durban (South Africa). These figures refer to wet waste. The waste collection and transportation processes for the two studies in the developing world were similar to those in the developed world (high collection rates, mechanized collection and transport and efficient local authorities) and might not be a true reflection on the majority of cities in the developing world and especially in Africa, where lower emissions (per tonne of waste) are expected due to the waste collection and transport process. On the other side, for the mechanized collection that exists in African countries, the age of the collection vehicles is much higher and there is lack of maintenance of the vehicle fleet which in turn might lead to higher emissions. For example, in Ibadan (Nigeria) the local authority had 45 collection vehicles servicing about 1.8 million people and 95% of these vehicles have been out of order, due to inadequate maintenance

(Ayininuola and Muibi, 2008). Henry et al. (2006) showed that in Kenya more than a third of the collection vehicles used by the largest five municipalities were out of service during the study year and most of the trucks were older than 10 years.

5. GHG emissions from waste disposal processes/technologies

The disposal of municipal waste in developing countries and in some of the developed countries is heavy reliant on landfills. It is considered that *the most common method of waste disposal in the developing countries is some form of landfilling* (UNEP, 2004) and this includes open uncontrolled dumps, as well as their more controlled and/or engineered counterparts. Other waste disposal technologies used in the developing world (i.e. incineration, composting, recycling and anaerobic digestion) has been also used and they also do produce GHG emissions. However, the amounts of greenhouse gases emitted due to these disposal technologies have been much lower and some of these processes could have important potential savings in terms of these emissions.

5.1. GHG from the decomposition of waste in landfills

The majority of studies investigating GHG emissions from waste management systems focused on landfills as the major contributing component, due to their methane emissions. Bogner et al.(2008) estimate that about 1.4×10^9 CO_2 e per year or 18% of the global anthropogenic methane emissions were due landfills and waste water treatment processes in 2004–2005. Developing countries have been estimated to account for about 29% of the global emissions, but this share is expected to increase rapidly reaching about 64% by 2030 (Monni et al., 2006). This is predicted due to growth in population and affluence, expansion of waste collection services and improved landfill management (i.e. change from dumps to sanitary landfills, most without landfill gas collection systems). Therefore, it is very important to understand these emissions and to focus mitigation initiatives in the waste sector on developing countries and their disposal facilities.

Methane emissions from landfills are routinely calculated and very rarely measured directly. The decomposing of waste in landfills and the resultant methane (and landfill gas) is calculated with the help of models which are used to summarize the very complex chemical and biological decomposition. Several such models (some simple, others complex), with different orders of kinetics have been developed, namely zero-order, first-order and second order models, as well as some more complex models (Kamalan et al., 2011). The most popular ones have been the first order models and overviews and formulae for the most used first order models (GasSim, LandGEM, TNO, Belgium, Afvalzorg, EPER and Scholl Canyon) have been presented by Kamalan et al. (2011) and by Thompson et al. (2009). In particular, a variation of the Scholl Canyon model has been used by the IPCC in their 1996 and 2006 guidelines on how to calculate methane from landfills (IPCC, 1996 and IPCC, 2006). These guidelines have been aimed at estimating GHG inventories from waste at national level and to report them in an internationally agreed methodology. However, the IPCC calculation model has also been used at a regional, municipal and landfill site scale (Weitz et al., 2008 and Wangyao et al., 2009) in developing countries.

There are a variety of factors which influence the generation of landfill gas and methane (Komilis et al., 1999), however, the three key factors for methane generation models for a landfill site are: the amount of waste disposed of in the landfill since commissioning, the degradable organic fraction of that waste and the decay rate (of each organic fraction and as a whole) (Thompson et al., 2009). Since for many developing countries records on the amounts of waste landfilled at a particular site, and in general, have not been always kept and the composition of the waste was not always known, in many cases estimations and extrapolations had to be used. Most notably, the IPCC guidelines IPCC 2006 established a method that can be applied to all countries/regions and provided default values (e.g. the regional generation rates as presented in Table 1), estimates and calculation methods to overcome lack of historical data. However, these estimates introduced higher uncertainty in the final results and countries with poor waste management data (which are mostly developing countries) have the highest uncertainties in their calculations. In the IPCC Guidelines (IPCC, 2006) uncertainties for global emissions from waste for developed countries with good data availability have been estimated to be 10–30% and for developing countries that do not have annual data it was estimated at 60% and above. These uncertainties have been traced back to the lack of data with regard to the amount and composition of the waste, but also to assumptions that have to be used (decomposition rates, methane generation rates, oxidation rates, capturing efficiency, etc.). In addition Lou and Nair (2009) highlighted that, in practice, the overall rate of emission for landfill gas can be also influenced by operational interventions, like waste compaction, leachate recirculation or aerobic landfilling and theoretically these factors should also be taken into consideration when modeling methane generation.

In general, the main criticism with regard to methane prediction models is their lack of accuracy and validation (Bogner and Matthews, 2003; Thompson et al. 2009, etc.). Thompson et al. (2009), for example, showed that although the four first order models investigated (LandGEM, TNO, Belgium and Scholl Canyon) *"have the same basic components with slight differences, their outputs vary considerably"*. This highlights why methane generation models have to be validated (i.e. predicted methane has to be compared with methane recovery data) and only a few, individual studies carried through this kind of investigation (e.g. Thompson et al., 2009 and Spokas et al., 2006). One of the more accurate methods to validate methane prediction models at landfill sites is the carbon balance approach (Spokas et al., 2006). This approach takes into account that the methane generated can be oxidized, recovered and stored within the landfill site. It can also migrate and only the remaining amounts are emitted into the atmosphere. Each component of the carbon balance can be quantified, modeled, engineered and optimized in order to reduce the amounts of methane emitted to the atmosphere. In particular, the capturing of landfill gas (for flaring and energy recovery), the oxidation of methane by using compost landfill cover, the pretreatment of waste and aerobic landfilling have been investigated as GHG mitigation strategies for landfills and have been covered in a review by Lou and Nair (2009). The implementation of such technologies in developing countries have been hampered by a series of factors, including lack of finance and capacity, however, with the implementation of the CDM projects a positive trend can be observed.

In developing countries the CDM projects sparked the use of the methane prediction models, carbon balances and their validation, because these processes were the prerequisites to predict the technical and financial feasibility of individual projects. Bogner et al. (2008) estimated that more than 105×10^6 CO_2 e per year are recovered from landfills world-wide. Methane recovery was initiated in the waste sector in 1975 and it is implemented (mandatory and voluntary) in many developed countries and in particular the USA. In developing countries it is also used and it became more financially feasible after the opening of the CDM process. Monni et al. (2006) predicted that in 2008 about 30×10^6 CO_2 e were recovered globally due to CDM projects in developing countries (representing about 28% of the global methane recovery). This figure does not include the offset energy due to the utilization of methane. Scenario modeling by the same authors showed the potential contribution that developing countries can play in the future, if gas capturing schemes continue to be implemented post 2012 (when Kyoto and CDM end) and an overall 15% global methane recovery rate is to be achieved (considered optimistic).

Unfortunately, the African continent lags behind and has the smallest numbers of CDM projects (in general and for the waste sector) registered or applying for registration (CDM Statistics, 2010; Couth and Trois, 2010 and 2011). Even so, out of the CDM work some regional validation will be possible for African countries and some model parameters could be customized in the future.

5.1.1. Calculated overall GHG emissions from landfill sites

The overall calculations for GHG from landfill sites involve a life cycle assessment approach which extended beyond the use of methane (and landfill gas) generation models and carbon balances, and included emissions from transport, the materials and energy used for constructing the site, the operation of the site, etc. Gentil et al. (2009) proposed the upstream-operating-downstream conceptual framework for accounting and reporting of GHG from waste, which takes into account direct and indirect emissions and savings. In this context, and taking a life cycle approach, Barton et al. (2008) compared GHG emissions for a series of generalized waste disposal scenarios applicable for developing countries. They have concluded that sanitary landfills with no landfill gas capture will have the highest GHG emissions (1.2 t CO_2 e per t of waste), followed by open dumpsites (0.74 CO_2 e per t of waste), sanitary landfills with gas collection and flaring (0.19 t CO_2 e per t of waste) and sanitary landfills with gas collection and electricity generation (0.09 t CO_2 e per t of waste). These figures are for wet waste. In their sensitivity analyses, the waste composition proved to be a critical factor and with waste composition moving towards a more developed country composition, the amount of greenhouse gases increased in both open dump and landfill without gas collection scenarios (mainly due to the increase in paper and textile). Therefore, this study underlined the increased emissions that developing countries will have if the waste is dumped or disposed as practiced currently.

In a generic study, Manfredi et al. (2009) calculated emission factors for landfills in developed countries (Europe) based on a lower biogenic carbon content of the waste. Although the boundaries were different, the results are in the same range of those presented by Barton et al. (2008) for developing countries. Open dumping (included only for comparison purposes) accounted for about 1 t CO_2 e per tonne of waste, sanitary landfills with gas collection and energy recovery accounted for 0.3 t CO_2 e per tonne of waste and low-organic-carbon landfills (for Europe, but not applicable for the majority of developing countries) for 0.07 t CO_2 e per tonne of waste. These figures refer to wet waste. No other scenarios were investigated. The study concluded that energy recovery is important and the actual amounts of GHG savings depend on what the generated energy substitutes. Another important conclusion was that stored biogenic carbon in landfills should be also considered, since it proves important in the European context. Manfredi et al. (2009) quantified greenhouse savings of 132–185 kg CO_2 e per tonne of wet waste in the European landfills. These conclusions are also valid for developing countries and they need further research for regional quantification.

Focussing on landfill sites alone, the international guidelines took into account methane emissions in different types of landfill sites including dumps, and a methane correction factor (MCF) is used for calculations and incorporated in the overall formulae for methane emissions (UNFCCC, 2008). The UNFCCC methodological tool used to determine methane emissions from disposal of waste at a solid waste disposal site (UNFCCC, 2008) which can be used with the IPCC first order decay model (IPCC, 2006) uses the following values for the methane correction factor for landfill sites:

- 1.0 for anaerobic managed solid waste disposal sites. These must have controlled placement of waste (i.e. waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include at least one of the following: (i) cover material; (ii) mechanical compacting; or (iii) leveling of the waste;
- 0.5 for semi-aerobic managed solid waste disposal sites. These must have controlled placement of waste and will include all of the following structures for introducing air to the waste layer: (i) permeable cover material; (ii) leachate drainage system; (iii) regulating pondage; and (iv) gas ventilation system;
- 0.8 for unmanaged solid waste disposal sites – deep and/or with high water table. This comprises all solid waste disposal sites (SWDS) not meeting the criteria of managed SWDS and which have depths of greater than or equal to 5 m and/or high water table at near ground level. The latter situation corresponds to filling inland water, such as pond, river or wetland, by waste;
- 0.4 for unmanaged-shallow solid waste disposal sites. This comprises all solid waste disposal sites not meeting the criteria of managed SWDS and which have depths of less than 5 m (UNFCCC, 2008).

5.2. GHG emissions from waste incineration

It is estimated that over 130×10^6 tonnes of waste are incinerated per year in over 600 plants world-wide (Bogner et al., 2008) and many developed countries derive significant benefits in terms of fuel replacement and energy from waste. However, controlled incineration as a method for waste disposal for municipal waste is not wide-spread in the developing world due to higher costs and unsuitable waste composition (high organic fraction, high moisture percentages and lower calorific value) (Barton et al., 2008). GHG emissions from incineration are considered small at around 40×10^6 tonnes CO_2 e per year (less than one tenth of the emissions from landfills) (Bogner et al., 2008). When accounting greenhouse gases from incineration the biogenic carbon is not included, and is being considered neutral. Therefore, only fossil carbon (from plastics, synthetic textiles, etc.) is accounted and reported (IPCC, 2006 and Astrup et al., 2009). In addition, the 2006 IPCC methodology specifies that for national inventories GHG emissions from the incineration of municipal waste are to be reported in the Waste sector if there is no energy recovery and under the Energy sector if there is energy recovery (IPCC, 2006).

Astrup et al. (2009) quantified greenhouse gases from incineration and co-combustion in the European context using the upstream-operation-downstream approach. They reported emissions from operations as 347–371 kg of CO_2 e per tonne of waste for incineration with energy recovery and 735–803 kg of CO_2 e per tonne of waste for co-combustion from municipal waste. However, there are savings of about −480 to −1373 kg of CO_2 e per tonne of waste from incineration with energy recovery and −181 to −2607 kg of CO_2 e per tonne of waste from co-combustion. In the developing world, for Taipei City, Chen and Lin (2008) report a saving of 222 kg of CO_2 e (or 0.06 MTCE) per tonne of waste from incineration with energy recovery. This value was calculated by a similar life cycle methodology to the upstream-operation-downstream approach followed by Astrup et al. (2009), however, the boundaries and the approach (generic vs case study) in the two studies are different. For the Taipei study the operational and transport emissions have been already subtracted from the savings. The generic European study and the figures calculated for Taipei show that in most cases (in developed and developing countries) GHG savings are larger than operational emissions and that incineration technologies can have substantial benefits in terms of energy generation and fuel replacement.

Another form of incineration which is practiced on a much larger scale in developing countries is the uncontrolled, open burning of waste. In developed countries this practice is prohibited. This kind of combustion is practiced at small scale (back-yard) and at larger scale (in landfills) and can be spontaneous (e.g. in poorly managed landfill sites due to methane) or set deliberately in order to reduce the volume of waste. Most of the studies on the topic of open burning of municipal waste are investigating the emissions of toxic compounds and the potential health risks they pose (e.g. Lemieux et al., 2004). There are no reported values for GHG emissions due to this activity at municipal level, however, the 2006 IPCC guideline (Chapter 5) contains a methodology for calculating GHG emissions from the open burning of waste to be applied for national inventories (IPCC, 2006).

5.3. Greenhouse gases from composting

Composting is used in both developed and developing countries as a way of dealing with the biodegradable fraction of their municipal waste (Bogner et al., 2008). Composting offers real advantages not only by reducing the volumes of waste but also by recycling nutrients and organic matter and improving soils. Since the decomposition process is aerobic, composting also generates less greenhouse gases as compared to landfilling. In Europe alone there are about 2000 composting facilities for household organic waste (Boldrin et al., 2009) and there is a successful policy to divert organic wastes from landfilling into composting. In developing countries composting should provide a viable alternative, because of the high biodegradable fraction of the waste. However, many of the large-scale, earlier initiatives involving composting in these countries (including Africa) failed and the smaller, decentralised operations seem to be currently more successful (Cofie et al., 2009). The CDM mechanism can also be used for composting in developing countries and a methodology has been developed for large scale projects (AM0025) and for small scale projects (AMS-III.F).

Currently there are two successful CDM municipal solid waste (MSW) composting projects in Africa. The first is in Cairo (Egypt) and involves mechanical and manual sorting of dry waste, followed by the shredding and turned windrow composting of the wet waste (UNFCCC PDD, 2007). The second CDM composting project is in Lagos (Nigeria) (UNFCCC PDD, 2009), and involves the shredding of unloaded waste followed by windrow composting. In addition, in Khartoum (Sudan) a composting plant is at planning stages (Tawfig et al. 2009).

In Europe and Australia composting has been used within the mechanical biological treatment technologies (MTB) for the stabilization of the organic fraction of the waste. The use of this compost is highly regulated in the OECD countries (UNEP, 2010). In some developing countries (e.g. Pudong, China) MTB technologies are also starting to be used (Hong et al., 2006).

Composting contributes to the release of GHG emissions, but more important it also saves such emissions and the actual amounts depend on a series of factors including waste composition (i.e. organic fraction), composting technologies, use of gas cleaning (i.e. for enclosed systems) and the actual use for the final product (Boldrin et al., 2009). Lou and Nair (2009) summarise the main theoretical and practical studies quantifying emissions from the composting process itself, showing that theoretical estimates (0.284–0.323 t of CO_2 e per tonne of waste) usually overestimate real, measured emissions (0.183–0.932 t of CO_2 e per tonne of waste). However, since the process is aerobic and emissions are of biogenic origin they are not accounted for and the emissions which really matter in the case of composting are the operational emissions. Lou and Nair (2009) also showed that greenhouse emissions are usually lower for windrows composting as compared to aerobic in-vessel composting due to lower energy requirements. They also underline that, although studies have shown that methane and nitrous oxide are produced during composting, they are usually not included in GHG accounting for this process.

Boldrin et al. (2009) present more detailed and extensive overall GHG emissions for composting and they do include methane and nitrous oxide emissions in an accounting methodology which uses the upstream-operating-downstream approach. They show that emissions can vary between −0.900 (net savings) to 0.300 (net load) t of CO_2 e per tonne of wet waste composted. They covered four composting technologies, namely open composting (windrow, static pile, mat), enclosed composting (channel and cell and aerated pile), reactor composting (tunnel reactor, box and container and rotating drum) and home composting. They show that the upstream contributions are very little, the operation contributions are moderate and the main burdens and savings in terms of greenhouse gases come from the use of the compost and what the compost substitutes. Other published results for developed countries (−183 kg of CO_2 e per tonne of waste for the USA (EPA, 2006) and between −32 to −58 kg of CO_2 e per tonne of waste for Europe (Smith et al., 2001) fall within the range calculated by Boldrin et al. (2009). These figures refer to wet waste. Quantification of greenhouse gases has been done only for the use of compost on land (replacing synthetic fertilizer) and peat substitution. Substitution of fertilizer is estimated to save about 8 kg of CO_2 e per tonne of wet waste composted and applied to land and substitution of peat will save about −4 and −81 kg of CO_2 e per tonne of wet waste composted (Boldrin et al., 2009). Farrell and Jones (2009) show that compost can be used for many other applications, most notably for remediation. The GHG emissions/savings from these uses are not quantified in the literature.

There are also a series of uncertainties with regard to GHG emissions from composting due to lack of scientific consensus (e.g. nitrous oxide emissions during compost use) or lack of actual data (i.e. for what the compost will be used). In particular, estimates and calculations for developing countries will have even more uncertainties included. It is considered that there is a paucity of specific data for composting in developing countries and studies done for these countries use data from literature (Boldrin et al., 2009). Calculations performed by Barton et al. (2008) for composting in developing countries in general, confirm this (i.e. the use of literature data) and the results in this case show that composting as process is carbon neutral. An almost zero effect of the composting process is also reported by Zhao et al. (2009) for Tianjin (China). They also show that, if kitchen waste (which represents about 57% of the waste) from this municipality is composted instead of landfilled, a 24% reduction in GHG emissions can be achieved. This illustrates the potential of composting in terms of greenhouse savings for municipalities in developing countries which have waste with a high organic content suitable for composting.

5.4. Greenhouse gases from anaerobic digestion

Anaerobic digestion has been defined as the anaerobic decomposition of organic wastes which produces biogas (methane and carbon dioxide) and biosolids (digestate) and as a waste management technology is practiced by both developing and developed countries. Developed countries, especially in Europe, have focused on high-tech plants and developing countries historically used low-tech smaller plants/reactors in which manure and other organic wastes were digested. However, in the last few decades a series of new local initiatives (plants/technologies) were introduced in developing countries, but not all were sustainable in the long term (Müller, 2007). Other (e.g. BARC (Mumbai), ARTI (Pune)) low tech anaerobic digestion technologies developed in these countries show real potential (Müller, 2007). Unfortunately, African countries are lagging behind with only a few experimental initiatives in this area (Müller, 2007). Most notably is the introduction in Tanzania of the ARTI system developed in India (Voegeli et al., 2009).

For the European context, Møller et al. (2009) assessed the overall GHG emissions from anaerobic digestion of source-separated municipal solid waste using the upstream-operating-downstream framework for the accounting of these gases. Their results showed that overall emissions from anaerobic digestion vary between a saving of −375 to a burden of 111 kg of CO_2 e per tonne of wet waste. The emissions from specific types of AD facilities varied between savings of −95 to −4 kg of CO_2 e per tonne of wet waste. They showed that, if an AD facility has high biogas production, substitutes CO_2-heavy electricity and exports heat, the savings could be substantial. However, if there are low methane yields, in connection with upgrading of biogas to vehicle fuel and high emissions of nitrous oxide from digestate, then a net burden will result (Møller et al., 2009). Smith et al. (2001) calculated slightly higher overall GHG savings for anaerobic digestion in the same geographical context. Their results ranged from −246 to −51 kg of CO_2 e per tonne of wet waste.

For developing countries in general, Barton et al. (2008) using a life cycle assessment estimated theoretical savings of – 210 kg of CO_2 e per tonne of wet waste due to the use of anaerobic digestion. More specifically for Tianjin (China), Zhao et al. (2009) calculated that anaerobic digestion is almost carbon neutral. In another case study for Phuket (Thailand) Liamsanguan and Gheewala (2008) calculated a saving of −30 kg of CO_2 e per tonne of wet waste treated by anaerobic digestion. Results from these studies in the developing world are within the range presented by Møller et al. (2009) for Europe. These differences in emissions are due to a variety of reason linked to the overall set-up and efficiency of the overall system. Biogas yields and the nature of the energy that this biogas use avoids play the most important role and will determine the ultimate savings.

Similar to composting, the overall quantification of greenhouse gases from anaerobic digestion has a high degree of uncertainty associated with it and Møller et al. (2009) identified the key parameters influencing emissions from anaerobic digestion. These are (1) substitution of energy or natural gas by biogas, (2) nitrous oxide emissions from digestate in soil, (3) fugitive methane emissions at the plant, (4) unburned methane during combustion, (5) carbon bound in soils and (6) fertilizer substitution. Some of these parameters are hard to quantify in developed countries, but even more so in developing countries, and even if case specific data is available, a certain degree of uncertainty will still persist (Møller et al., 2009).

5.5. Greenhouse gases from recycling

There is agreement in the literature (e.g. EPA, 2006; Smith et al., 2001; Christensen et al., 2009) that recycling of fractions of municipal waste offers some of the highest benefits with regard to GHG savings from waste. Recycling is practiced by both developed and developing countries and differences (legal, social, economic and technical) have been noted in the literature (e.g. van Beukering and van den Bergh, 2006) and Uiterkamp et al., 2011). Recycling is a complex waste management issue which is beyond the scope of this paper; however, in terms of GHG emissions it presents definite advantages for all municipalities in all countries.

Different greenhouse savings have been reported for different recycled materials and Table 3 presents a summary from the published literature. As it can be seen from this table the greenhouse savings from recycling vary for each of the materials considered. However, the most common themes when investigating these variations are energy and the different variations in the downstream substitution in the use of the recycled material. As can be seen from Table 3 there is agreement that recycled aluminum has the highest potential savings in term of greenhouse gases, followed by steel, plastics, paper and glass, which show some of the lowest savings.

The savings due to recycling are expected to be higher in the developed world and in particular in those countries which rely on coal as a predominant source of energy. South Africa is such a country, as are India and China. Therefore, to quantify savings from waste recycling more precisely, country specific and even region specific saving factors should be calculated also for developing countries in a similar fashion as those for Europe and the USA (see Table 3). So far there are no such recycling factors for the developing countries, and in the few studies from the developing world quantifying savings from recycling the EPA (2006) factors from Table 3 are used (e.g. Chen and Lin, 2008; Friedrich and Trois, 2008 and Chintan, 2009). In general, there is a paucity of life cycle assessment studies in the developing world as compared with developed countries, and these studies are used in the quantification of greenhouse gases from more complex waste management systems. The literature review conducted by the authors for this study alone yielded about 40 research articles, peer reviewed publications and reports for developed countries and only about 10 for their developing counterparts. In particular, Africa seems to lack such studies.

Two other issues pertinent to recycling in developing countries and the emissions of greenhouse gases are the export/import of recyclables to and from developing countries and the role of the informal sector in recycling. The export and import of recyclable and recycled materials to and from developing countries is becoming important in a globalised world. For example, in South Africa in 2009, 73 tonnes of recycled paper were imported and 17 tonnes of recycled paper were exported (PRASA, 2010) with the country being a small player in the recyclables market. In general, recycled materials are exported to developing countries from the developed world. An example is the UK where during 2007 4.7×10^6 tonnes of paper and 0.5×10^6 tonnes of plastics recycled in this country were exported to China (WRAP, 2008) and therefore the transport of these recyclables over long distances might reduce the greenhouse savings substantially. However, this seems to be case

Table 3
Greenhouse gas savings from recycling different fractions of municipal waste (expressed as tonne of CO_2 e per metric tonne of waste unless otherwise specified).

Waste fraction/material	Smith et al. (2001) for Europe	EPA (2006) for USA[a]	Other authors (European context)
Paper – mixed	−0.60	−3.19 (−0.96)	−390 to −4.40 (Merrild et al., 2009)
Plastics – HDPE	−0.49	−1.26 (−0.38)	−1.27 to −0.99 (Astrup et al., 2009)
Plastics – PET	−1.76	−1.40 (−0.42)	
Glass	−0.25	−0.27 (−0.08)	−0.50 to −1.50 (Larsen et al., 2009b)
Ferrous metal (steel)	−1.48	−1.63 (−0.49)	−0.56 to −2.36 (Damgaard et al., 2009)
Aluminium	−9.07	−12.31 (−3.70)	−5.04 to −19.34 (Damgaard et al., 2009)

[a] Original values (EPA, 2006) expressed in MTCE/tonne (US) are presented in brackets.

specific. A study done by WRAP (2008) for the export of recyclables from the UK to China showed that in general less than a third of the CO_2 emissions are due to transport. These emissions drop to less than 10% if taking into account the fact that a large number of ships return empty from the UK to China. This conclusion might not be generalized and it depends on the mode of transportation and the waste transported (Salhofer et al., 2007) and more research is needed in this area. Increased quantities of electronic waste are exported to African countries (Schmidt, 2006) where the waste is further processed for recycling and it causes an array of environmental and health problems (Nnorom and Osibanjo, 2008 and Robinson, 2009).

The informal recycling sector (i.e. waste pickers who salvage recyclables in the waste management system) in developing countries plays an important role in reducing greenhouse gases as shown by Chintan (2009) for India. For Delhi alone about 962×10^3 tonnes CO_2 e was saved by the informal sector recycling, which achieved very high recovery rates (e.g. mixed paper 95%, mixed plastic and metals 70% and glass 75%). These informal GHG savings compare favorably with other formal initiatives (CDM projects for waste-to-energy and composting) being more than three times greater (Chintan, 2009). In addition to GHG savings, the informal recycling sector supplied an income for about 15 million waste pickers in 2007 alone and brought other advantages to the formal waste management system at local level (e.g. reduced volumes of waste, savings on costs for collection, transport and disposal, extended life of a landfill) (Wilson et al., 2006 and Medina, 2008). However, these marginalized groups are not supported by authorities, lack access to finances (e.g. carbon trading scheme) and are in conflict with formal reduction projects (e.g. access to recyclables is reduced in the case of waste to energy projects). A similar situation with regard to informal recycling is reported for the African countries (Ball et al., 2007) including South Africa (Oelofse and Strydom, 2010), however, there is a lack of information on the quantities recycled by the informal sector as well as on the other advantages due to this activity. Furthermore, the South African recent legislation (Waste Bill – Act 59 of 2008) does not recognize the role of waste pickers in municipal waste management.

6. Conclusions

This review paper compared the GHG emissions from different municipal waste management processes in developing and developed countries, with particular emphasis on the African continent and South Africa. What sets developing countries apart are the different motivational factors for GHG accounting and reporting. Developing countries do not have a mandatory obligation to report GHG and there are less data and information for waste management in general and in particular for the quantification of greenhouse gases. In the absence of such data, a variety of assumptions have to be used, which affects the accuracy of calculations and makes validation of results a very challenging process. One example of such an assumption is the waste generation rate for African countries (IPCC, 2006) which currently seems to be over-estimated. In addition, the GHG emissions from waste management in developing countries are predicted to increase exponentially. Therefore, more attention has to be paid to how these emissions arise, are accounted/calculated and reported for waste management processes in the municipalities of developing countries.

When investigating GHG emissions from individual processes there is agreement on the magnitude of the emissions expected from each process (generation of waste, collection and transport, disposal and recycling). Recycling brings about the highest savings in terms of GHG, followed by composting and incineration with energy recovery. The disposal of waste in landfills has some of the highest GHG emissions. In particular, in developing countries these emissions are dominating due to the methane released by dumpsites and landfills. If these are upgraded to sanitary landfills these emissions will continue increasing, unless the methane is captured and either flared or used for electricity generation. The CDM projects have made some in-roads with regard to the waste to energy projects, however, the African continent lags behind. The GHG emissions from transport and collection are lower in developing countries due to inadequate provision of these services, in particular in African cities which have some of the lowest collection rates.

The investigation of GHG emissions from individual waste management processes, which make up a waste management system, show that the few values (e.g. GHG emissions for landfilling or transportation) calculated for developing countries are within the range reported for developed countries. However, one has to be critical of these results, because there are no calculations done for the elements/processes found only in developing countries (e.g. non-motorized transport of waste). A direct comparison of GHG emissions from waste management in different municipalities should be undertaken only at process level. At systems level such comparisons should be undertaken with care, because the determining waste management factors (e.g. waste composition, collection rates, waste management process, etc.) are different and so could be the accounting methodology used. Therefore, there is a need to develop a common approach applicable for developed and developing countries for the accounting of greenhouse gases from waste management at municipal level and individual processes should be the foundation blocks.

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