Carbon Footprint of the Solid Waste Sector in Greater Bangalore, India

T. V. Ramachandra, K. Shwetmala and T. M. Dania

Abstract Every day, Bangalore generates approximately 3,000–4,000 tonnes of waste. A major fraction (72 %) of total waste is organic or wet waste, which degrades in the natural environment. This study is focused on the estimation of the carbon footprint of household waste generated in Bangalore city. The results from two theoretical estimation methods, mass balance approach and default methodology, are compared with the measurement results derived from experimental values. Experiments revealed an emission of 0.013 g CH_4/kg of organic fraction of municipal solid waste and 0.165 g CO_2/kg, which is much lower compared to the Intergovernmental Panel on Climate Change method (0.036 kg CH_4/kg of waste) or theoretical approaches (0.355 kg CH_4/kg, 0.991 kg CO_2/kg of waste). From the elemental composition and general theoretical chemical equation of aerobic and anaerobic degradation of waste amounts, total methane and carbon dioxide were estimated to be 670,950 and 1,870 tonnes per day (tpd) by the mass balance approach, which are considerably higher than the 87.32 tpd of methane emission determined using the default methodology. These values are still higher than the

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experimental estimated values of methane and carbon dioxide. The total carbon footprint of municipal solid waste generated from the city is 361 kg/day of CO_2 equivalent in the environment.

KeyWords Municipal solid waste · Carbon footprint · GHG emissions · Waste treatment · Bangalore

1 Carbon Footprint of Solid Waste

Carbon footprint (CF) refers to the direct or indirect emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) expressed in terms of carbon dioxide equivalents (Wiedmann and Minx 2007). This constitutes a vital environmental indicator to understand and quantify the main emission sources and is an effective tool for energy and environmental management. GHGs get into the atmosphere either due to natural sources or anthropogenic activities. The contribution from natural sources is minimal and is neutralised due to the natural environmental processes, but a large quantity is generated from anthropogenic sources, which is accumulating in the atmosphere. Intergovernmental Panel on Climate Change (IPCC) lists 17 GHGs with different global warming potentials in a 100-year time horizon (IPCC 1996). The United Nations Framework Convention on Climate Change (UNFCCC) considers only carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) in accounting national GHG inventories (UNFCCC 1997).

Carbon footprint assessment for a region h elps to determine the impact of human activities on the environment and global climate. The major sectors and activities included in the inventory for estimating the carbon footprint are listed in Table 1. This chapter focuses on the quantification of the carbon footprint in the domestic solid waste sector. Mismanagement of municipal solid waste is a vital source of anthropogenic GHGs, such as methane (CH_4), biogenic carbon dioxide (CO_2), and nonmethane volatile organic compounds (NMVOCs) (Ramachandra 2009). Among these, methane is considered to be a potent GHG, having a global warming potential (GWP) that is 25 times greater than that of carbon dioxide. The concentration of atmospheric methane is annually increasing at 1–2 %, which necessitates the quantification of the carbon footprint in the waste sector for planning appropriate mitigation measures.

A major fraction (72–79 %) of solid waste generated in Indian households is organic (Jha et al. 2008; Thitame et al. 2009; Ramachandra 2009, 2012). The quantity and composition of emission mainly depends on the quantity of organic waste and method of solid waste disposal. Indiscriminate disposal of waste without treatment (segregation of organic fraction and generating either energy or compost) produces GHGs, thus contributing to the carbon footprint. Methane is

Table 1 Carbon footprint sector description

Sector	Activities included
Energy	Emissions of all greenhouse gases resulting from stationary and mobile energy activities, including fuel combustion and fugitive fuel emissions
Industrial processes	By-product or fugitive emissions of greenhouse gases from industrial processes not directly related to energy activities, such as fossil fuel combustion
Solvent and other product use	Emissions, of primarily nonmethane volatile organic compounds, resulting from the use of solvents and N_2O from product uses
Agriculture	Anthropogenic emissions from agricultural activities, except fuel combustion, which is addressed under Energy
Land-use change and forestry	Emissions and removals of CO_2, CH_4 and N_2O from forest management, other land-use activities, and land-use change
Waste	Emissions from waste management activities

Source IPCC/UNEP/OECD/IEA 1997

produced during the anaerobic degradation or breakdown of organic waste or carbon dioxide during aerobic degradation or burning of waste.

2 Solid Waste

Solid wastes are any non-liquid wastes that arise from human and animal activities that are discarded as useless or unwanted. These are the organic and inorganic waste materials such as product packaging, grass clippings, furniture, clothing, bottles, kitchen refuse, paper, appliances, paint cans, batteries, etc. produced in a society, which do not generally carry any value to the first user (Ramachandra 2009). Municipal solid waste (MSW) is composed of wastes generated from residences, markets, hotels and restaurants, commercial premises, slums, street sweeping and parks. Bangalore residences contribute 55 % to the total waste, which is the highest among all sources (Chanakya and Sharatchandra 2005; Ramachandra 2011; Ramachandra et al. 2012). The waste generated from hotels and eateries form about 20 %, fruit and vegetable markets contribute about 15 %, trade and commerce about 6 %, and street sweeping and parks about 3 % (Table 2). The slum areas contribute only 1 % of total, because the slum population in Bangalore is low compared to other metropolitan cities, such as Mumbai, Delhi, or Kolkata. The slum populations in Mumbai, Delhi, Kolkata, Chennai, and Bangalore are 49, 19, 33, 18 and 8 % (Census of India 2001), respectively. MSW generation for Kolkata, Chennai, Delhi, and Mumbai are 2653, 3036, 5922 and 5320 tpd, respectively. The contributions of slums to the total MSW generated in these cities are approximately 875.49, 546.48, 1125.18, and 2606.8 tpd for Kolkata, Chennai, Delhi, and Mumbai, respectively.

Table 2 Municipal solid waste generation in Bangalore

Source	Quantity (t/d)	Composition (% by weight)
Domestic	780	55
Markets	210	15
Hotels and eatery	290	20
Trade and commercial	85	6
Slums	20	1
Street sweepings and parks	40	3

Source Chanakya and Sharatchandra 2005; Lakshmikantha 2006; Ramachandra 2009

Waste management strategies of these waste sources may vary with quantity and composition of waste.

3 Quantity and Composition of Solid Waste

3.1 Current Rate of Waste Generation

Greater Bangalore is the administrative, cultural, commercial, industrial and knowledge capital of the state of Karnataka, India with an area of 741 sq. km. It lies between the latitude 12°39′00–13°13′00″ N and longitude 77°22′00″–77°52′00″ E. Bangalore city administrative jurisdiction was redefined in the year 2006 by merging the existing area of Bangalore city spatial limits with eight neighboring Urban Local Bodies (ULBs) and 111 Villages of Bangalore Urban District. Bangalore has grown spatially more than 10 times since 1949 (~69–716 sq.km) and is the fifth largest metropolis in India, currently with a population of about 9 million. Bangalore city population has increased enormously from 65,37,124 (in 2001) to 95,88,910 (in 2011), accounting for 46.68 % growth in a decade. Population density has increased from 10,732 (in 2001) to 13,392 (in 2011) persons per sq. km. The per capita GDP of Bangalore is about $2066, which is considerably low with limited expansion to balance both environmental and economic needs (Ramachandra et al. 2012a).

The spatial increase in city area and increase in population have increased the total amount of MSW from 650 (in 1988) to 1450 tpd (in 2000). The current estimates indicate that about 3000–4000 tonnes of MSW are produced each day in the city—the daily collection is estimated at 3600 tpd (Ramachandra et al. 2012). The increase in the per capita generation from 0.16 (1988) to 0.58 kg/d/person (2009) is due to the changes in consumption patterns. Changes in composition are noticed recently with the increasing quantity of waste.

Table 3 Physical composition of municipal solid waste in Bangalore

Waste type	Composition (% by weight)						
	Domestic	Markets	Hotels and eatery	Trade and commercial	Slums	Street sweepings & parks	All sources
Fermentable	72	90	76	16	30	90	72
Paper, cardboard	8	3	17	56	2	2	12
Cloth, rubber, PVC, leather	1		0.3	4	0.5	0	1
Glass	2		0.2	0.7	8	0	1
Plastics	7	7	2	17	2	3	6
Metals	0.3		0.3	0.4	0.2	0	0.2
Dust and sweeping	8		4	8	57	5	6

Source TIDE 2000

3.2 Composition of Solid Waste

Usually, municipal solid waste can be broadly categorised into organic or inorganic waste using major components of solid waste composition. Organic waste is also known as wet waste, whereas inorganic waste is also known as dry waste. Inorganic waste includes both recyclable and nonrecyclable materials, whereas organic waste includes all the waste components that can degrade in natural environments, such as leftover food, vegetables, and fruit peels. Municipal solid waste is a heterogeneous mixture of solid materials that does not have any use to society. Food waste, plastic, paper, rubber, leather, glass and textiles are the common MSW components. Sourcewise solid waste composition is shown in Table 3. Waste composition changes with the source of generation, but most of the sources generated a major fraction (>70 %) of organic waste. It is evident that Indian waste has more organic than inorganic constituents, except slums and commercial places.

Solid wastes generated in Indian cities are mainly composed of organic fractions and are biodegradable. The waste generally includes degradable (paper, textiles, food waste, straw and yard waste), partially degradable (wood, disposable napkins, and sludge) and nondegradable materials (leather, plastics, rubbers, metals, glass, ash from fuel burning such as coal, briquettes or woods, dust and electronic waste) (Jha et al. 2008; Visvanathan 2004).

Most (72–79 %) municipal solid waste is organic (Ramachandra 2009; Ramachandra 2011; Sathishkumar et al. 2001; Ramachandra et al. 2012; Sharholy et al. 2007; GOI 1995). The contribution of inorganic components is gradually changing and is likely to show further changes in the future. The biodegradable fraction is quite high, arising from the practice of using fresh vegetables in India. The plastic and metal contents are lower than the paper content and do not exceed 1 %, except in metropolitan cities. This is mainly because large-scale recycling of these constituents takes place in most medium and large cities. The composition of

MSW at generation sources and collection points determined on a wet weight basis consists mainly of a large organic fraction (70–75 %), ash and fine earth (5–8 %), paper (10–14 %) and plastic, glass and metals (each less than 3–5 %) (Ramachandra et al. 2012). Paper waste generally falls in the range of 3–7 %, when the waste reaches the disposal site (Asnani 1998). The organic fraction is high (>80 %) in many pockets within many South Indian cities, such as Chikkamagalur, and is largely represented by vegetable, fruit, packing, and garden waste (Chanakya et al. 2009). The physical composition of MSW in Bangalore is as follows: paper 8 %, textiles 5 %, plastic 6 %, metals 3 %, glass 6 %, ash fine earth and others 27 %, and compostable matter 45 % (CPCB 1999; Sharholy et al. 2008). In Bangalore, organic waste mainly consists of vegetable and fruit wastes; its percentage contribution ranges between 65 and 90 % (Rajabapaiah 1988; TIDE 2000; Ramachandra 2009; Chanakya et al. 2009). Many studies have been conducted in academic institutions to determine the waste composition. As shown in Table 4, the organic fraction ranges from 72.5 (Sathiskumar et al. 2001), 79.6 (Ramachandra et al. 2012), and 88 % (Rajabapaiah 1995).

3.3 Factors/Variables of Changes in Quantity and Composition

Waste quantity and composition depends upon various factors such as country, topography of the area, different seasons, food habits, commercial status and activities of the city (Jha et al. 2008; Thitame et al. 2009; Ramachandra 2009), and standard of living. The relative percentage of organic waste in MSW is generally increasing with the decreasing socio-economic status; rural households as well as low- and mid-income urban households generate more organic waste than urban households.

4 Solid Waste Management

Municipal solid waste management (MSWM) is associated with the control of waste generation—its storage, collection, transfer and transport, processing, and disposal in a manner that is in accordance with the best principles of public health, economics, engineering, conservation, aesthetics, public attitude, and other environmental considerations. Presently, most of the metropolitan cities and MSWM systems include all the elements of waste management. However, in the majority of smaller cities and towns, the MSWM system comprises only four activities: storage, collection, transportation, and disposal (Sharholy et al. 2008; Ramachandra 2009; Ramachandra 2011)

Table 4 Studies on waste composition (%) of Bangalore

Study area waste type	Beukering (1994) Bangalore	TIDE (2000) Bangalore	Sathish Kumar et al. (2001) IISc	CPCB (2004-05) Bangalore	BBMP (2008) Bangalore	Ramachandra et al. (2012)	Ramachandra et al. (2012) IISc
Glass	0.24	1.43	–		3	1.4	0.5
Plastic	0.48	6.23	9	22.43	12	6.2	12.7
Paper/cardboard	3.12	11.6	18		13	11	6.2
Metal	0.05	0.23	–		1	1	0.2
Organic	57.04	72	73	51.84	59	72	79.59
Other	38.08	6.5	–			6.5	0.28

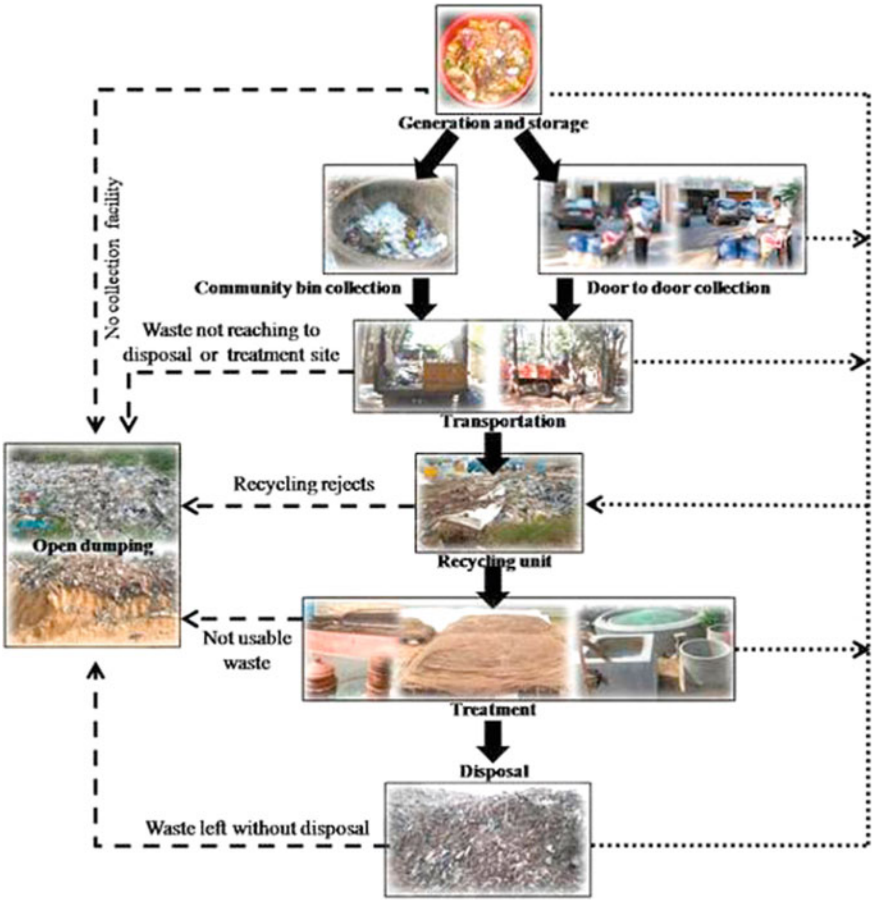

Fig. 1 Functional elements of solid waste management

A solid waste management (SWM) system refers to a combination of various functional elements (Fig. 1) associated with the management of solid wastes; details are provided in Table 5. The system, when put in place, facilitates the collection and disposal of solid wastes in the community at minimal costs, while preserving public health and ensuring little or minimal adverse impact on the environment. The functional elements that constitute the system are shown in Fig. 1.

Table 5 Wardwise auditing of functional components of municipal solid waste management

Function	Technique		Shivajinagar	Malleswaram	Koramangal	IISc	HMT	Airport road	Chickpet	Average (%)
Storage	Community bin	Percentage of covered bins	30	–	–	33	–	–	84	49*
Collection	Community bin	Percentage of area covered in commercial area	40	0	0	–	–	–	30	17.5**
	Door to door	Percentage of area covered in residential areas	100	100	100	60	100	100	100	94.29
		Percentage of waste segregated	0	0	20	5	0	0	0	3.57
Transfer		Transfer station	A	A	A	A	A	A	A	A
Transport	Truck	Truck with mesh (%)	100	100	100	75	100	100	100	96.43
		Truck with mesh and polythene cover (%)	75	40	75	0	0	0	100	41.43
Process	Percentage of waste recycled	Informal	18	18	18	18	18	18	18	18
		Formal								
	Percentage of waste composted				22					3.14
	Percentage of waste for anaerobic digestion									
	Percentage of waste incinerated									
Disposal	Sanitary landfill									
	Dump yard		85	85		85	85		85	60.71
	Quarry				63			85		21.14

A = Absent
* Only the areas having bins are taken into consideration
** Only the commercial areas have been taken into consideration, i.e. Shivajinagar, Malleswaram, Kormangala, and Chickpet
Source Ramachandra and Bachamanda 2007

4.1 Generation and Storage

Waste generation quantity and composition depends on the lifestyle of households. Segregation at the generation or source level is to divide the waste into different categories, such as organic waste and inorganic waste. In the conventional method, partial segregation of newspaper, milk pouches, etc. happens at the house level, but the rest gets mixed up during waste storage. In places with the active participation of nongovernmental organizations and the community, segregation at source/house level is in place (Pattnaik and Reddy 2009; Ramachandra 2009). However, it is still at a very preliminary stage. Informal recycling plays an important role in waste segregation and waste management (Sudhir et al. 1996). Storage of waste means the temporary containment of waste, at the household or community levels. At household level, old plastic buckets, plastic bins, and metal bins are used for storing waste; at the community level, wastes are stored in masonry bins, cylindrical concrete bins, and metallic and plastic containers (Joseph 2002; Kumar et al. 2009). Stored waste is then collected and transported to the transfer station or processing site at regular intervals.

4.2 Collection

Waste collection is the removal of waste from houses and all commercial places to a collection site, from where it will go for further treatment or disposal. Its efficiency is a function of two major factors: workforce and transport capacity (Gupta et al. 1998). Community bin and door-to-door collection are prevalent in India (Kumar et al. 2009; Kumar and Goel 2009; Pattnaik and Reddy 2009; Ramachandra 2009). Indian cities are shifting from community bin collection to door-to-door collection to improve the existing waste management system. Most of the cities are either fully or partially covered with door-to-door collection (Kumar et al. 2009). The door-to-door collection facility is only limited to 60–61 % of the present collection system in Kolkata (Chattopadhyay et al. 2009; Hazra and Goel 2009), whereas in Bangalore it has reached up to 94–100 % of total waste collected from residential areas (Ramachandra and Bachamanda 2007; Kumar et al. 2009).

4.3 Transportation

Transportation of the stored waste to final processing sites or disposal sites at regular intervals is essential to avoid bin overflow and littering on roads. Usually, light and covered vehicles with carrying capacities of around 5 tonnes per trip are used for transportation of waste (Rajabapaiah 1988; Ramachandra 2009). In small towns, bullock carts, tractor-trailers, tricycles, etc. are mainly used for transportation (Sharholy et al. 2008).

4.4 Treatment (Aerobic and Anaerobic)

Treatment is required to alter the physical and chemical characteristics of waste for energy and resource recovery and recycling. The important processing techniques include compaction, thermal volume reduction, manual separation of waste components, incineration, anaerobic digestion, and composting. The organic fraction of the waste is processed either through composting (aerobic treatment) or biomethanation (anaerobic treatment). Composting through aerobic treatment produces stable product-compost, which is used as manure or as soil conditioner. In metropolitan cities, compost plants are underutilized for various reasons, including unsegregated waste and production of poor quality of compost, thus resulting in reduced demand from end users (Kumar et al. 2009; Chattopadhyay et al. 2009; Ramachandra 2011). Vermi-composting is also practiced at few places. Biomethanation through microbial action under anaerobic conditions produces methane-rich biogas. It is feasible when waste contains high moisture and high organic content (Chanakya et al. 2007; Kumar and Goel 2009). Recyclable waste that can be transformed into new products such as plastic, rubber, glass, metal, and others are collected separately and auctioned by recycling industries (Agarwal et al. 2005).

4.5 Disposal

Waste disposal is the final stage of waste management. As in urban areas, uncontrolled and unscientific disposal of all the categories of waste, including organic waste, has lead to environmental problems, such as contamination of land, water, and air environment, in larger towns or cities, the availability of land for waste disposal is very limited (Gupta et al. 1998; Mor et al. 2006; Ramachandra 2009). In many places, a major fraction of urban wastes are directly disposed in low-lying areas or in hilly areas at city outskirts (Lakshmikantha 2006; Talyan et al. 2008; Chattopadhyay et al. 2009). In this backdrop, MSW rule 2000, Government of India (GOI) was introduced to regulate all components of waste management. Landfilling or disposal is restricted to nonbiodegradable, inert waste and other wastes that are not suitable either for recycling or for biological processing as per MSW rule 2000.

5 Mismanagement of Waste and Its Implications

Municipal solid waste management is initiated by urban local bodies to protect the environment and the society from adverse impacts of increasing waste quantity. However, mismanagement of municipal solid waste, either due to lack of adequate workforce or disregard of a vital functional element in SWM, creates serious health and environmental implications. Mismanagement in handling solid wastes include (i) mixing of organic and inorganic wastes, (ii) open solid waste dumping, (iii) unscientific/indiscriminate waste disposal practices, and (iv) burning of solid waste.

5.1 Mixing of Organic and Inorganic Waste

Segregation of organic and inorganic waste at the source level is the most critical stage regarding waste management and recycling processes. If the waste is not separated properly, it reduces the recyclability of waste and increases the volume of waste for transport and at treatment and disposal locations. Biodegradation of waste under anaerobic conditions, it releases methane; under aerobic conditions, it releases CO_2 to the environment. Apart from these, leachate from waste dumps contaminates the soil and groundwater resources.

5.2 Open Solid Waste Dumping

Bangalore generates around 3000–4000 tonnes of solid waste daily, and a major constituent is organic (72 %). The quantum of wastes generated is far greater than the capacity of the three permitted waste treatment and disposal sites at Mavallipura, Mandur, and Singehalli. Because these locations are quite far-off, many of the trucks dump at unauthorized locations such as roadsides, lake beds, vacant plots, etc. to reduce their transportation costs. The disposal of waste at private or public places in and around cities—(i.e., on locations other than the designated urban solid wastes processing sites) is termed unauthorised dumping.

The waste is collected by outsourced agencies that dispose waste in vacant places within the city as well as at outskirts/peri-urban areas. Most dumps inside the city are small and waste is dumped at the respective locations for 1–2 days. However, dumps at outskirts are large (>25 hectares) and waste is being dumped there because longer time and organic fractions are degraded with leachates getting into soil. Figure 2 provides the spatial locations of open dumps.

Wastes are dumped in public and private open lands, agricultural land, road sides, and at hilly areas with no provision for controlling gaseous emission or leachate. Most of the organic wastes are reduced by animals, and a fraction undergoes microbial degradation. Both aerobic and anaerobic degradation takes place in open disposal sites. Methane recovery attempts were reported from two open landfills in Nagpur, India (Bhide et al. 1990).

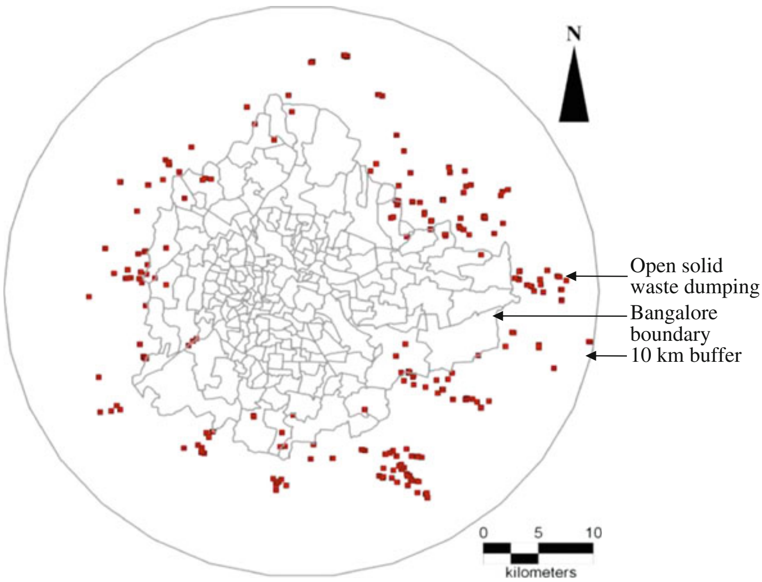

Fig. 2 Open dumpsites located around in and around Bangalore

5.3 Unscientific Waste Disposal Practice in Landfill

Sanitary landfills with options for collecting leachate and gas emissions are essential for safe waste disposal. Waste is compacted and daily covered with a layer of soil. During the final closing, the landfill site is effectively capped with a thick soil layer. All these factors lead to anaerobic conditions inside the landfill site and hence continuously produce methane gas. Waste composition and the age of landfill site are two main factors that influence the extent of methane production. However, sites earmarked for disposal of solid waste in most Indian cities do not adhere to the environment norms. Landfills with unscientific waste disposal practices are evident from the direct dumping of mixed wastes. These sites are not properly covered with soil with no appropriate collection system for leachate and gaseous emission. Also, these sites receive more waste than the capacity, disturbing the whole system at disposal site.

5.4 Burning of Solid Waste

The burning of municipal solid waste at waste disposal sites or at open dump sites is common to reduce the volume of waste or to segregate the metal items from mixed accumulated waste. Usually, this type of incomplete combustion can reduce

40–60 % of waste volume. Incomplete combustion of waste during open burning contributes to GHG emissions and other air pollutants. The carbon in MSW has two distinct origins. One is harvested biomass sources, such as yard trimming and vegetable/fruit residues, whereas the second is non-biomass sources such as plastic and synthetic rubber derivatives (EPA 2006). MSW burning results in emission of CO_2 and N_2O. The carbon stored in harvested biomass sources also is lost in the atmosphere, which can be recycled back to the system.

So the waste management practices of concern for methane emissions are open dumping, which is generally practiced in developing regions, and sanitary landfilling, which is generally practiced in developed countries and urban areas of developing countries (IPCC 1996). Aerobic waste treatment or composting of organic waste emits an almost negligible quantity of methane, as waste gets converted and increases the soil organic matter. Anaerobic waste treatment or biomethanation of waste generates significant quantities of methane, but this methane is collected and used as a source of energy.

6 Method for Determining CF of Solid Waste

Total CF of the waste sector was 23,233 CO_2 equivalent, which included municipal solid waste disposal (53 %), domestic waste water, industrial waste water, and human sewage (Garg et al. 2006). In 1990, the CF of the waste sector was 14,133 CO_2 equivalents (ALGAS 1998) which increased to 28,637 CO_2 equivalent in 2000 (Sharma et al. 2006). These estimations were based on IPCC emission factors in the absence of local emission factors. In this chapter, different techniques adopted for the estimation of CF are compared along with field experiments to assess the validity of theoretical estimates. Experimental methods have been developed to estimate the emissions from organic waste and composting processes at local levels.

There are a number of methods to estimate the carbon footprint in terms of methane emissions from solid waste disposal methods. These methods are broadly classified into (i) theoretical estimations and (ii) experimental methods. Accuracy of theoretical estimations depends on the availability of data. Usually, the available theoretical estimation methods are mass balance approach, default methodology (using degradable organic carbon content), theoretical first-order kinetics, and the triangular method (IPCC 1996; Kumar et al. 2004; Garg et al. 2006; Sharma et al. 2006).

6.1 Theoretical Estimation Methods

6.1.1 Mass Balance Approach

Mass balance approach is the simplest level of emission estimation. Its use is generally discouraged because it gives a high estimation of emissions. This method does not include any factors and does not distinguish between various types of disposal sites. In this approach, theoretical emissions are calculated using stochiometric equations as per Tchobanoglous et al. (1993). Equations for aerobic and anaerobic degradations considering complete degradation of waste are given by Eqs. 1 and 2.

$$C_{2.98}H_{0.462}O_{1.02}N_{0.099} + 2.659\ O_2 \rightarrow 2.98\ CO_2 + 0.0825\ H_2O + 0.099\ NH_3 \tag{1}$$

$$C_{2.98}H_{0.462}O_{1.02}N_{0.099} + 2.4287\ H_2O \rightarrow 1.1978\ CH_4 + 1.2143\ CO_2 + 0.099NH_3 \tag{2}$$

6.1.2 Default Methodology

This approach of emission estimation considers the degradable organic carbon content of MSW (Eq. 3) and does not include changes in the conversion of carbon to methane emissions with time (Bingemer and Crutzen 1987; IPCC 1996).

$$\begin{aligned} CH_4(\mathrm{Gg/yr}) = {} & MSW_T \times MSW_F \times MCF \times DOC \times DOC_F \times F \times (16/12 - R) \\ & \times (1 - OX) \end{aligned} \tag{3}$$

where MSW_T = Total municipal solid waste generated, MSW_F = Fraction of MSW disposed of at the disposal sites (0.6), MCF = Methane correction factor (0.6), DOC = Degradable organic carbon (0.18), DOC_F = Fraction of DOC dissimilated (0.77), F = Fraction of methane in LFG (0.5), R = Recovery of LFG (0), and OX = Oxidation factor (0).

6.1.3 First-Order Kinetics

First-order kinetics consider the availability of time series waste disposal data and other detailed informations for a disposal site to compute the methane emission as the degradable organic components degrade slowly and methane is emitted over a long period.

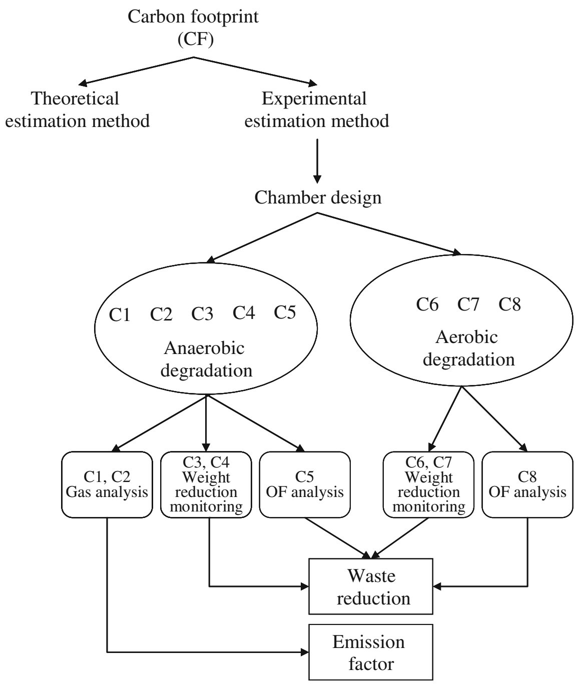

Fig. 3 Flow chart of experimental setup

6.1.4 Triangular Method

The triangular method considers time-dependent release of gaseous emission based on first-order decay. Total gaseous yield is computed for the organic fraction considering rapidly biodegradable waste and slowly biodegradable waste. This requires extensive waste characterization and quantification at the waste disposal site (Kumar et al. 2004).

6.2 Experimental Estimation Method

The elemental composition of the organic fraction of the MSW is presented as $C_5H_{8.5}O_4N_{0.2}$ (Bizukojc and Ledakowicz 2003). The degradable organic carbon decomposes by microorganisms under aerobic or anaerobic conditions. In aerobic conditions, carbon gets converted into carbon dioxide; in anaerobic conditions, it gets converted into carbon dioxide and methane, which are GHGs.

Methane and carbon dioxide are measured and quantified at the laboratory scale through waste degradation under aerobic and anaerobic conditions. This process involves design of a chamber, monitoring, and quantification of emissions, as shown in Fig. 3.

Fig. 4 Gas collection chamber

6.2.1 Design of Chamber

The gas analysis chamber was made up of glass with diameter of 7 and 20 cm height. The shape of the chamber was conical with a gas collection apparatus. The gas collection apparatus was round in shape, with seven openings for gas collection (Fig. 4). These openings were closed with rubber leads. In anaerobic conditions, collection openings were closed; for aerobic conditions, openings were left open. There were eight chambers; C1, C2, C3, C4, C5, C6, C7 and C8. Chambers C1, C2, C3, C4 and C5 were maintained under anaerobic condition, whereas chambers C6, C7 and C8 were maintained in aerobic conditions without any external aeration. Chamber C1 and C2 were used for gas analysis, whereas C3, C4, C6 and C7 were used to monitor weight reduction with time and C8 and C5 were used for organic fraction (OF) analysis. Anaerobic chambers were covered with paper and kept away from sunlight to give optimum conditions of anaerobic degradation. In aerobic chambers, the lead was open to provide conditions similar to open dumpsites.

6.2.2 Monitoring Duration for Waste Degradation

The experiment was started with 200 g of sample kept in each of the eight chambers (Fig. 5). Degrading samples were subjected to organic fraction analysis, gas analysis and weight reduction study. For organic fraction analysis, waste samples were collected on days 0, 3, 6, 9, 12 and 17 (Chanakya et al. 2007).

Fig. 5 Waste sample used for experiment

6.2.3 Organic Fraction Analysis

In organic fraction analysis, parameters such as temperature, moisture content, total solids, volatile solids, carbon, hydrogen, and nitrogen were measured.

pH: 3 g of dried sample was added to 15 ml of distilled water and shook for 24 h to determine pH with a pH meter.

Moisture content: To obtain dry mass, the solid waste material was weighed (W_1) and then dried (W_2) in an oven at 105 °C until the mass of the dried material became constant. The moisture content is computed by Eq. 4.

$$\% \text{ moisture content } = ((W_1 - W_2)/W_1 \times 100) \tag{4}$$

Total solids: 5 g of sample was weighed (W_2) in an empty crucible (W_1) and dried in an oven maintained at 105 °C for 24 h (W_3). Percent of total solids (TS) was calculated using Eq. 5.

$$\% \text{ TS } = ((W_3 - W_1)/(W_2 - W_1) \times 100) \tag{5}$$

Volatile solids (VS): This was measured in accordance with APHA (1975). Approximately 2–3 g of an oven-dried sample was weighed (B) in an empty crucible (A) and heated to 550 °C for 1 h in the muffle furnace (C). Percent VS was calculated using Eq. 6.

$$\% \text{ VS } = ((B - C)/(B - A) \times 100) \tag{6}$$

CHN analysis: Carbon, hydrogen, and nitrogen (CHN) was analyzed with the help of CHN analyser (LECO elemental analyser). After finding the CHN of the sample, the elemental composition of waste under the study was determined with the help of the equation given by Tchobanoglous et al. (1993). Elemental composition was used for determining the theoretical estimation (mass balance approach) of gaseous emission during waste degradation in the aerobic and anaerobic processes.

Fig. 6 Gas collection from compost plant

6.2.4 Gas Analysis: *Gaseous Composition*

Gas analysis was carried out using a gas chromatograph (ProGC, Mayura Analytical Pvt.Ltd., India) equipped with flame ionisation and thermal conductivity detectors. All hydrocarbons are separated by a Heysep-R column having a mesh size of 80/100 and dimensions 2 m × 1/8in. Detection is done by FID detector. Analysis of gas was done on every 14th day. After 15 days, with the decrease of gas production with time, samples were collected at the gap of 7 days. Gas was collected in 10-ml syringe and then subjected to gas chromatography.

Quantification of gaseous emission: Quantification of gaseous emission was done using the water displacement method. In the water displacement method, samples were connected through a burette filled with potassium dichromate solution. As gas enters and passes through the burette, it displaces filed potassium dichromate solution in the burette. The volume of solution displaced is equal to the volume of gas produced from waste samples. After the 30th day of the experiment, the volume of gas was measured in chambers.

6.2.5 Weight Reduction Study

Chamber samples were weighed on a balance on days 0, 3, 6, 9, 12, 17 and 30 to check subsequent reductions in the total waste quantity kept on day 0.

Analysis of composting process: Composting is an aerobic process of organic waste treatment. During the composting process, waste gets converted into compost or manure. Particularly, the carbon content of waste gets converted to humus or emitted into the environment as carbon dioxide. To assess emissions from composting, the experiment was carried out in the compost unit that is successfully implemented and managed at Vellore city. City municipal waste in Vellore has been treated since 2009 through the aerobic option (compost). There were 17 working compost pits for residential waste. Gas samples were collected (Fig. 6)

Table 6 Change in total solids of waste (%)

Sl. No.	Days	Aerobic	Anaerobic
1	3	93.45	93.07
2	6	92.74	92.99
3	9	87.67	93.88
4	12	91.92	86.80
5	17	93.25	86.66

from compost processes happening in Vellore city. Compost chambers filled at different time intervals were selected to see the difference in emissions and other properties as these pits were filled in different months and are at different stages of degradation. These experiments were done during 2010 (Jan–May) and also verified later (June 2013).

7 Results and Comparison of Different Findings for CF of Solid Waste

7.1 *Change in properties of waste*

The initial pH of 4.06 in waste samples suggests the initiation of degradation. Fresh organic fractions of MSW will have pH in range of 6–7 (Bizukojc and Ledakowicz 2003). The initial temperature was 28 °C and during the degradation; the temperature in the anaerobic chamber was 24.5–26 °C in all samples. Anaerobic digestion occurs under two temperature regimes: mesophilic (between 20 and 45 °C, usually 35 °C) and thermophilic (between 50 and 75 °C, usually 55° C). The sample temperature was found to range from 25 to 29.5 °C (mostly above 28 °C) on all sampling days under aerobic conditions; this is because the heat formed was easily getting dissipated into the atmosphere because the sample quantity was small and kept open. The total solid content of waste was decreasing with time (Table 6). The percentage of carbon in the preliminary sample was about 42 %, which was highest among the three elements, with nitrogen 1 % and hydrogen 6 %. Results of CHN analysis on different sampling days showed that carbon varied from 46 to 49 %, hydrogen 6–7 %, and nitrogen 1–2 % in aerobic conditions. At the laboratory scale, total wet waste reduction in aerobic degradation was found to be 25 times faster than anaerobic degradation.

Table 7 Emission from anaerobic degradation of waste (in 30 days)

Chamber	Waste quantity (kg)	CH4 (ml/kg)	CO2 (ml/kg)	Total (ml/kg)
C1	1	22.527	134.379	156.906
C2	1	12.875	33.275	46.150
Avg	1	17.701	83.827	101.528

7.2 Emission Factor (Based on the Experiment)

Total gas produced from 30 days of continuous degradation of 1 kg of waste under anaerobic condition is 101.528 ml, which consisted of 17 % of methane and 83 % of carbon dioxide (Table 7). The emission factors for gaseous emissions of methane and carbon dioxide were 0.013 and 0.165 gm/kg, respectively. (Because gaseous volume was in millilitre, it was converted into gaseous mass using gas volume and the respective density at standard temperature and pressure: Density = Mass/Volume, with the density of methane and carbon dioxide as 0.716 and 1.965 g/l, respectively.) Total daily emissions from the organic fraction of solid waste degradation in Bangalore are 31.06 and 403.52 kg of methane and carbon dioxide, respectively.

7.3 Comparison of Emissions Computed Using Different Methods of Estimation

7.3.1 Determination of Emissions by Mass Balance Approach

The elemental composition of the sample was found to be comparable with the literature. According to Reinhart (2004), the elemental composition of sample was 1.30, 0.07, and 0.17 of carbon, nitrogen, and hydrogen, respectively. From stoichiometric calculations it can be seen that 1.1978 mol of methane and 1.2143 mol of carbon dioxide is emitted from 1 mol of analysed sample ($C_{2.98}H_{0.462}O_{1.02}N_{0.099}$) under anaerobic conditions. Thus, 0.355 kg of CH_4 and 0.991 kg of CO_2 are emitted from 1 kg of waste sample. Similarly, under aerobic conditions, carbon dioxide emissions were found to be about 2.431 kg/kg of waste. Therefore, the total emissions from Bangalore solid waste using mass balance approach in anaerobic conditions is 869.75 tpd of methane and 5955.95 tpd of carbon dioxide.

7.3.2 Default Methodology

In the estimation of methane emission potential by the IPCC default method, the amount of solid waste that is available for anaerobic degradation and methane generation was assumed as 100 %. The result shows that there was about 87.32 tpd

Table 8 Comparison of emission factors

Gaseous emission	Mass balance approach (kg/kg)	Default methodology (kg/kg)	Experimental estimation method (gm/kg)
CH_4	0.355	0.036	0.013
CO_2	0.991		0.165

Note Default method of IPCC accounts for only CH_4

of methane potential for the city, which is less than estimated emission from the mass balance approach. If we compare methane emission from each kilogram of organic waste, then through this method estimated methane emission will be 0.036 kg/kg of waste.

7.3.3 Experimental Estimation Method

In contrast to the theoretical estimation method, in which methane emission potential is calculated based on the amount of waste being disposed every day, the theoretical methods overestimate emission values, necessitating quantification of methane emission at the laboratory scale. Total methane emission from Bangalore solid waste using the experimental emission factor is 31.06 kg/day, whereas carbon dioxide is 403.52 kg/day. Results are much lower than theoretically estimated values because these methods assume that all potential methane is released as it comes in contact with the environment. Also, quantified values are lower than the emission estimated at landfills in Chennai by Jha et al. (2008). Landfills with mature waste enhance the methane emissions from fresh waste under anaerobic conditions.

Table 8 shows a comparison of emission factors computed by different methodologies. It is clear from comparison of emissions computed from different methods of estimation that the theoretical estimation method overestimates the emission from waste in comparison to laboratory-estimated or field-estimated values. Still further, more accurate estimation is possible using an accurate quantity of waste for different treatment methods, as well as by knowing emission from open dump and unscientific disposal at landfill site at more controlled conditions.

7.4 Ward-Wise CF of Solid Waste Using Experimental Values

Every day Bangalore generates around 3,500 tonnes of municipal solid waste. Of that, 55 % is from household waste (Table 2), with per capita generation of 0.35 kg/day of domestic waste.

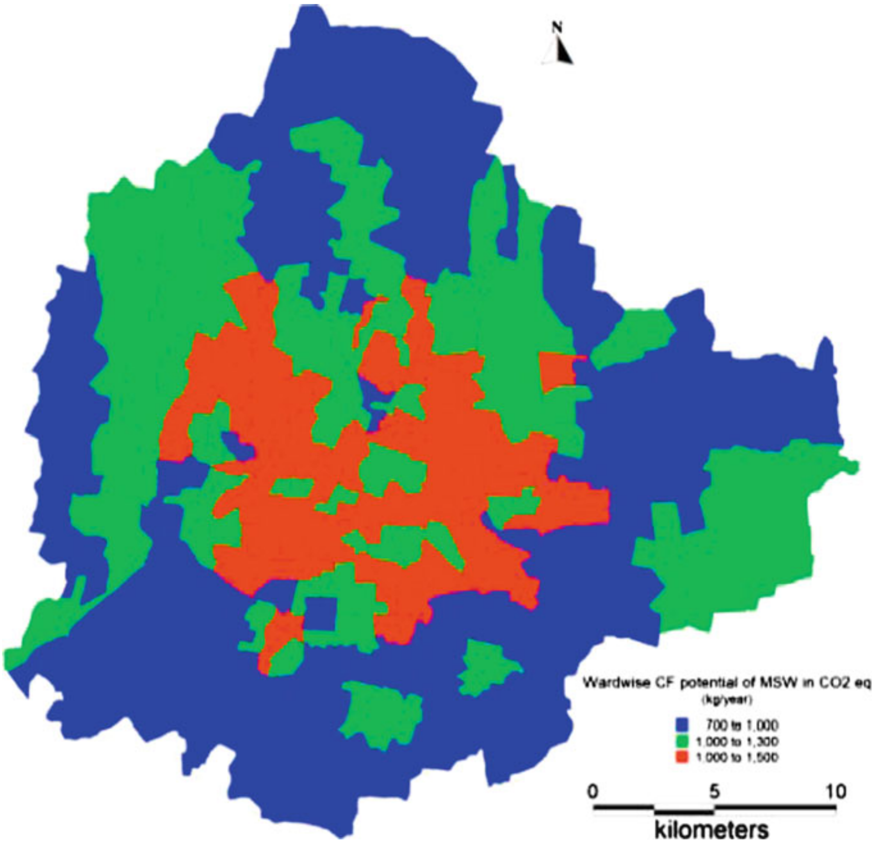

Fig. 7 Carbon footprint of municipal solid waste

7.5 Carbon Footprint of Municipal Solid Waste

Estimated methane and carbon dioxide emission from representative waste samples were used for computing annual emissions from solid waste. Total ward-wise organic waste generated is 2044 tpd. Methane and carbon dioxide emissions are 19.13 and 242.83 kg/day. Methane emission values were multiplied by 21 to compute the carbon footprint of waste. Annual carbon footprint of municipal solid waste is 644.61 kg/day of CO_2 equivalent, assuming that total waste generated in the city is reaching to waste disposal sites without any treatment. City wards where the population is less dense have less emissions than densely populated ward (Fig. 7). Most of the core city wards are densely populated, so their carbon footprint potential is more than other wards of the city. Figure 7 illustrates the pattern of open dumping, which is prevalent at outskirts.

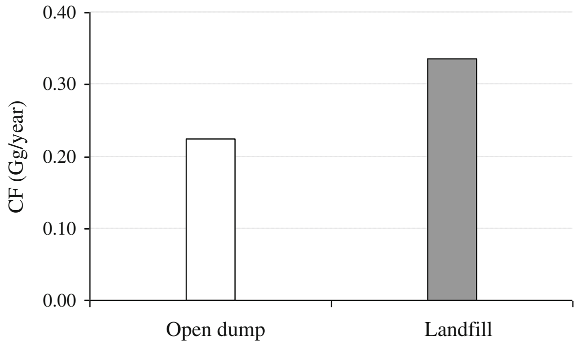

Fig. 8 Annual carbon footprint considering open dumpsites

Table 9 Emissions from air samples collected near a compost plant

Plant (residence time of waste)	Sample vol. (cm^3)	CH_4 (%)	CO_2 (%)	CH_4 ml/cm^3	CO_2 ml/cm^3
60 days	5722.65	0.02	0.23	0.0000034	0.0000401
30 days	1130.4	0.018	0.144	0.0000159	0.0001273
10 days	1844.7	0.038	0.4	0.0000205	0.0002168

7.6 Carbon Footprint of Open Dumps: Unauthorized Locations

An earlier study reported the existence of 60 open dumpsites around the city (Lakshmikantha 2006). Field work conducted in 2010 showed a considerable increase in open dumps across the city and outskirts (Chanakya et al. 2011). Quantification of dumps shows that there are 270 dumps (Fig. 2) distributed in all four zones of the city. Waste quantity is determined through the visual estimates at each location (supplemented by photographs of each site). A total of about 83,557 tonnes wastes are scattered in and around Bangalore city. The average life of an open dump is 2–3 years. Based on field investigations during 2011 and 2012, about 40 % of daily waste is being dumped at unauthorized locations (Fig. 2). Figure 8 illustrates the carbon footprint of unauthorized dumps and authorized dumps (with minimal or no treatment) based on the quantity and emission factor.

7.6.1 Characteristics of Composting and Its Emission Potential

The percentage of carbon dioxide and methane emitted from a compost plant is far less than that emitted from chambers under anaerobic condition. Among the three compost samples, samples from plant (with residence time of 10 days) show higher gas emission (as it is the new pit among the three) of 0.0000205 ml methane and 0.0002168 ml carbon dioxide (Table 9). The sample from compost of

60 days has relatively lower gas emission, due to the presence of mature waste. BMP analysis further corroborates this result, as there is no gas production from compost samples.

8 Mitigation Measures

Carbon footprint quantifications reveal that GHG emissions are mainly due to mismanagement (absence of recovery and treatment of organic fractions) of municipal solid waste. Hence, mitigation of GHG emissions (CH_4 and CO_2) from municipal solid waste involves (i) reduction of the quantity of waste, (ii) segregation of organic fractions of wastes, and (iii) treatment of waste to recover energy (biomethanation) or resources (compost —aerobic treatment). Reduction of waste generation is possible through reduced waste generation, segregation at source level, reuse, and recovery of waste. Composting and anaerobic digestion are treatment options for organic waste (which constitute 70–75 % of the total), whereas recycling is used for inorganic materials (15–18 %). Wastes that cannot be treated or recycled are ultimately disposed at disposal sites or landfills. Segregation at the source with treatment at local levels (ward levels) plays a prominent role in minimizing organic fractions getting into disposal sites.

An integrated solid waste management (ISWM) approach would aid in the mitigation of GHGs emitted into the atmosphere by open dumping or by unscientific disposal of waste in landfill site. ISWM includes source segregation, regular collection of waste, treatment of organic fractions at local levels, and disposal of only inert refuse at landfill sites. The organic fraction is the major contributor of GHGs in MSW and has to be treated for energy and resource recovery. Reduction of GHGs through biogas generation is the most common clean development mechanism approach for emission mitigation in India. Residential associations in select wards of Bangalore have successfully adopted ISWM through source segregation at household levels, recovery of recyclables, and composting of organic fractions, etc. These ventures have successfully demonstrated that sensible waste management, which includes a reduction in the carbon footprint at local levels, could be economically viable for entrepreneurs due to the market potential for composts and recyclables (bottles, plastic, paper, metal, etc.).

9 Conclusions

The direct or indirect emissions of carbon dioxide, methane, and other GHGs, expressed in terms of carbon dioxide equivalents, indicate the CF of a region, which constitutes a vital environmental indicator to mitigate global warming and consequent changes in the climate. This study indicated that the theoretical estimation of emissions from solid waste is much higher than the experimentally determined value. Total emissions from ward-wise waste of the city are 19.13 and 242.83 kg/day of methane and carbon dioxide, respectively. Reduction of waste generation is possible through reduced waste generation, segregation at source level, reuse, and recovery of waste. Composting and anaerobic digestion are treatment options for organic waste (which constitute 70–75 % of the total), whereas recycling is used for inorganic materials (15–18 %). Wastes that cannot be treated or recycled are ultimately disposed at disposal sites or landfills. Segregation at the source with treatment at local levels (ward levels) plays a prominent role in minimizing organic fractions getting into disposal site.

GHG emission factors vary with methodology. Experiments conducted reveal an emission of 0.013 gm of CH_4/kg of organic fraction of municipal solid waste and 0.165 gm CO_2/kg, which is much lower compared to the IPCC method (0.036 kg CH_4/kg of waste) or theoretical approaches (0.355 kg CH_4/kg, 0.991 kg CO_2/kg of waste). The current work provides emission factors at local levels, which could help in the accurate quantifications of emissions. Nevertheless, a comparative analysis of commonly used methods (such as IPCC) with the experimental value highlights the overestimation of GHGs from the waste sector with the techniques adopted earlier.

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