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Municipal solid waste: Generation, composition and GHG emissions in Bangalore, India

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ABSTRACT

Municipal solid waste in developing countries mainly consists of degradable materials (> 70%), which plays a significant role in GHG (Greenhouse gas) emissions in urban localities. The increasing municipal solid waste generation along with the high fraction of organic waste and its unscientific disposal is leading to emission of GHG (methane, CO_2, etc.) in the atmosphere. Proportion of municipal solid wastes collected by the agencies disposed at identified sites is about 60%, while the balance is disposed-off at unauthorized disposal sites leading to the environmental consequences including greenhouse gas emissions. Mitigation strategy necessitates understanding of composition of waste for its treatment and management in an environmentally sound way. The study revealed that the per capita waste generated is about 91.01 ± 45.5 g/day with the per capita organic waste generation of 74 ± 35 g/person/day. The household per capita waste generation was positively related with income and education levels, while negatively related with family (household) size. The organic fractions constitute 82% with the strong recovery potential and conversion to energy or compost range. The total organic waste generated is about 231.01 Gg/year and due to mismanagement consequent emissions are about 604.80 Gg/year. Integrated solid waste management strategy is suggested to manage the organic fractions through technology and policy interventions, which helps in mitigating GHG emissions with potential economic benefits.

1. Introduction

Solid wastes are any non-liquid wastes that arise from human and animal activities and are discarded as useless or unwanted. These include both organic and inorganic fractions such as kitchen refuse, product packaging, grass clippings, cloth, bottles, paper, paint cans, batteries, etc., produced in a society, which do not generally carry any value to the first user [1]. Solid waste generated in the municipality, encompasses heterogeneous and homogeneous wastes from urban, peri-urban regions [1–3]. 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. MSWM is considered a serious environmental challenge confronting local authorities [2,4]. Environmentally sound municipal waste management now become a global challenge due to limited availability of resources, increasing population especially in developing countries, unprecedented and irreversible urbanization and industrialization. Currently, several countries have realized that the way they manage their solid wastes does not satisfy the objectives of sustainable development throughout the world [5,6].

Unplanned urbanization coupled with rapid population growth and changes in the standard of living in urban centres of India have led to the tremendous increase in the amounts of municipal solid waste (MSW) leading to mismanagement, which include mix of dry and wet wastes (due to insufficient segregation), dumping in drains and open spaces, disposal without treatment for energy or resource recovery. More than 90% of the MSW generated in India is disposed on land in an unscientific and unacceptable way [7]. Of which major portion (70–75%) of municipal solid waste is organic [1,4,8,9] and contribution of inorganic component is gradually changing and is likely to show

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further changes in the future. However, solid waste management still has gaps due to lack of waste segregation at source level, treatment, reuse, recycling and appropriate disposal.

Treatment of organic fraction of waste alters its physical and chemical characteristics for energy and resource recovery. The important processing techniques include either composting (aerobic treatment) or bio-methanation (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 due to various reasons, most important reasons are unsegregated waste and production of poor quality of compost resulting in reduced demand from end users [2]. Vermi-composting is also practiced at few places. Bio-methanation through microbial action under anaerobic conditions produces methane rich biogas. It is feasible when waste contains high moisture and high organic content. Uncontrolled and unscientific disposal of all the categories of waste including organic waste leads to the environmental problems such as contamination of land, water and soil environment due to leaching of nutrients, etc.

Mismanagement of solid waste has led to public health risks, adverse environmental impacts, haphazard landfilling leads to depreciate the water quality and other socio-economic problems [10–12]. The problems derived from solid waste have a unique and complicated character; and untreated waste are the potential source of pollution. The organic fraction of waste through treatment forms a secondary source of raw materials.

Dumping of waste in unauthorized place is also one of the common practices in urbanizing cities of developing countries as there are lacunae in the implementation of MSW rules. Solid waste management to be effective requires separation of waste at source level with the implementation of 3Rs (reduce, reuse and recycling), treatment of organic fractions of wastes at local levels and disposal at sanitary landfills [2,13]. The indiscriminate dumping, inadequate treatment and poor recovery of organic fractions in urban areas have caused adverse effects on the local ecology, environment (such as air, water and land pollution) and human health [14–21]. The sustained dumping of solid waste without treatment has overloaded the assimilative capacity of the surrounding environment, necessitates environment friendly solid waste management.

Appropriate waste management policy needs to be based on the principles of sustainable development, which considers the society's refuse as a potential resource. Solid waste management (SWM) facilities are crucial for environmental management and public health in urban regions. Techniques for solving regional waste problems inevitably have a large number of possible solutions due to variable population densities, incomes, multiple (actual and potential) locations for waste management infrastructure, protected landscape areas and high value ecological sites. Due to this, municipal solid waste management have received a great deal of attention as the country produces an estimated quantity of 50–600 million tonnes of urban solid waste annually. Environmentally sound waste management depends on various site-specific factors such as the characteristic of the waste, the efficiency of the waste collection from the source level and processing systems required by different waste management practices, availability of proximity of material for recovery from the waste stream, the emission standards to which waste management facilities are designed and operated, the cost effectiveness of the environmental obtained by different management practices and social performance of the community.

The waste generation quantum depends mainly on the consumption patterns, seasons, lifestyle and socioeconomic factors. The per capita waste generation is expected to increase annually by 1.33% [22–24]. Table 1 lists the quantity of waste generated in the metro cities of India, which highlight that the waste quantity generation is high in Chennai, Greater Bangalore and Greater Mumbai due to the standard of living and urbanization. However, waste generated is comparatively low in the Pune and Lucknow [1,25]

Table 1
Quantity of MSW generation rate in Metro cities.
Source: Ramachandra [1,2]; Chanakya et al., [53].

Sl. No	Name of city	Waste quantity (TPD)
1	Greater Bangalore	1800 −3600
2	Greater Mumbai	3200
3	Ahmadabad	1200
4	Kanpur	2142
5	Lucknow	600
6	Chennai	1819
7	Pune	1000

Mismanagement of municipal solid waste is a vital source of anthropogenic greenhouse gases (GHG) such as methane (CH_4), biogenic carbon dioxide (CO_2) and non-methane volatile organic compounds (NMVOCs) etc., [1,26,27]. Among these, Methane is considered as a potent Greenhouse gas (GHG) having global warming potential (GWP) 25 times greater than that of carbon dioxide and concentration of atmospheric methane is annually increasing at 1–2% [28–30]. Emission of methane from landfill accounted 3–9% of the anthropogenic source in the world [28,31].

The organic components in the waste dumps and landfills generate about 60% methane and 40% carbon dioxide (CO_2) together with other trace gases during anaerobic decomposition [32,33]. This would vary depending on the waste composition, age, quantity, moisture content and ratio of hydrogen/oxygen availability at the time of decomposition [33].

2. Literature review

Solid waste generation at household has been studied in many countries. For example, survey of waste generation and the relationship with the socioeconomic factors in households of Beijing, China [34] shows waste generation at 0.23 kg/capita/day with 221 kg/m^3 bulk density, 50% moisture content with negative relationship between daily per capita generation of household waste and socio-economic factors viz., household size and income. Similar study in parts of Makurdi, urban city in north central Nigeria [35] shows that 82% is organic with bulk density of 200 kg/m^3. Per capita waste generated across sectors varies evident from 0.54 kg/cap/day in household, 0.018 kg/m^2/day in commercial, 0.015 kg/m^2/day institutional and 0.47 kg/m^2/day in small and medium scale industries.

Quantification and assessment of characteristics of waste through door-to-door survey during two seasons (dry season and wet season) in the Can Tho city the capital of the Mekong Delta region [6] shows that an average household solid waste generation is about 285.28 g/person/day (including 283.10 during dry season and 287.46 g/person/day). Statistical analysis reveals household quantity waste is positively correlated with the population density, urbanization level and negatively correlated with household size. Total greenhouse gas baseline emission by the household solid waste is estimated as 153.41 t per day carbon dioxide equivalent, while compostable and recyclable accounted 80.02% and 11.73% respectively. The composition and properties of the household waste of Hangzhou, China [36] show that food leftovers make high proportion (64.48%) followed by plastics, paper, glass, textiles, metals, wood and bamboos. The composition of food and dry waste are 31.8% and 45.3% respectively and high rate of dehydration was obtained at 19.21% wet wastes by the combined food waste dehydration system.

The analysis of household waste generation and characteristics in Cape Haitian city [37] based on waste collected from 116 households for 21 days, show that average waste generation is about 0.21 kg/capita/day. Organic and inorganic waste accounts about 65.5% and 34.5% respectively. The bulk density, moisture content and LCV was found to be 0.26 t/m^3, 55.9% and 1395 kcal/kg respectively. Estimation of the emission of methane from municipal solid waste disposal sites by using default, modified triangular methodology and by field investigation [31], show methane emission of 14.206 Gg, 7.667 Gg and 1.776 Gg respectively.

The greenhouse gas emission from municipal solid waste management in Indian mega-cities, Chennai [33] based on IPCC (Intergovernmental Panel on Climate Change) tier I and tier II methods for estimating the CH_4 emission for the year 2000 from Kodungaiyur (KDG) and Perungudi (PGD) landfill sites, show CH_4 emission of 8.1 Gg (for KDG with the waste of 314 Gg) and 9.8 Gg (for PGD with the waste of 379 Gg) respectively. Emission fluxes were estimated by using Gas chromatography (GC-SRI, USA, Model 8610 C) flame ionization detector and with the knowledge of an area of landfills, CH_4 annual emissions of 0.12 Gg y^{-1}, N_2O emission of 1 $ty^{-1}$and 1.16 Gg y^{-1} CO_2 emissions. Evaluation of the quantitative and qualitative characteristics of MSW in Allahabad city [21] through door-to-door survey show the average generation rate varies from 0.37 kg/capita/day to 0.44 kg/capita/day and the total quantity of MSW is about 500 t/day. Sujauddin et al., [38] assessed the quantitative and qualitative aspects of solid waste and its management through the compilation of socioeconomic data at household level and daily solid waste traits. Structured questionnaire based survey of 75 households at Rahman Nagar, Residential Area, Chittagong, Bangladesh during May to October 2006, and reveal the generation of waste as 1.3 kg/household/day and 0.25 kg/person/day. The vegetables were dominant i.e., 62% among samples and was highest (88%) in low socioeconomic group and lowest (47%) in high socioeconomic group. The organic fraction is positively correlated with family size, education level and income.

Further, Sankoh et al., [39] assessed the relevant socioeconomic factors affecting household waste generation and composition in Freetown, Sierra Leone through the door-to-door survey using pre-tested and structured questionnaire in four selected constituencies of the city covering 130 households. The data analyses reveal that the average family size was 7.64 persons with 4.18 persons per room, 36.5 years was the average age of the family, 3.82 persons per household was the employment status with the average monthly income of Le 740454 and average solid waste generation rate was 5.98 kg/household/day and 1.66 kg/person/day. The generation of household waste is positively correlated with average family size, employment status, monthly income, educational level, number of room(s) occupied and negatively correlated with the average age of family size and marital status. Getahun et al., [3] investigated the household, institutions, commercial area and street sweeping waste quantity, composition and current disposal practices in jimma through the compilation of data on socioeconomic factors revealed that daily average generation rate of solid waste and per capita waste was found to be 88,000 kg and 0.55 kg/person/day respectively. Family size was positively correlated with total waste generation rate and educational status of households was negatively associated with the total waste generation. Also the daily waste generated in wet season is higher than the dry season and monthly family income and educational status of waste generators have significant relationship with type of disposal systems.

Ramachandra and Varghese [40] explored the possibilities of achieving sustainable management of solid waste using Bangalore as a case study. The strategies include community participation, human resource development, legal mandates and adopting recent technologies like GIS-GPS integrated management System. Environmental audit of municipal solid waste management for Bangalore city was done by Ramachandra and Bachamanda [41] by collecting the data from government agencies, field survey and interview with stakeholders. Identified and assessed the unauthorized dumping sites in three segments, inside core area, the region between the core area and city boundary and peripheral area of the city up to buffer distance of 10 km from city boundary during April 2010 to April 2012.

Swethmala et al., [42] Identified unauthorized dumping site using GPS and Google Earth images. Spread area was determined by visually estimating the length and breadth of dump while composition was determined based on visual inspection of 5–6 random region of dump site. A total 696 dump locations were identified, from that experts randomly verified more than 269 locations across all four quadrants of city. Of 269 sites, 193 sites lying within the core city and 76 sites were found outside the core city boundary and 33 sites were found at outskirts of the city. The average intensity of dumps was 0.55, 0.69, 0.82 and 1.23 dumps/km^2 in North-East, South-East, South-West and North-West zones respectively. The number of dump sites was highest in NW (212) though NW quadrant is closet to only authorized waste processing site. Among these, 73.9% had construction debris followed by plastic waste and small extent of organic waste. The temporal changes in dump sites shows that new dump sites were created constantly in study area where as older dumps are being abandoned. In the second year survey, found 452 locations were visited in grids, found about 125 new dump locations and 327 old dump location. About 128 earlier dump site now turned up construction of new building. The average intensity of dumpsites was 0.69, 1.1, 0.69 and 0.41 dumps/km^2 in NW, SE, SW and NW respectively.

Earlier studies focused mainly on the aspects such as composition, generation and disposal of MSW in Bangalore. This includes various waste handling practices [8], exploring options for handling wastes at decentralised levels [25,40], comparative assessment of community bins and beneficial aspects of door to door collection systems, etc. These efforts have not captured the relationship between socio economic factors and solid waste generation (SW), and its last stage of the life cycle in Bangalore city. Further, the growing concern of greenhouse gas emissions necessitated the quantification of waste and GHG emissions with options to mitigate environmental implications. In this regard, the main objective of the present study is to i) determine the composition of waste and the rate of generation of HSW, ii) SWM being practised at household level iii) assess GHG emissions from the household solid waste and iv) capture the role of various socioeconomic factors that affect the generation, composition and management of solid waste at household level.

3. Data and method

3.1. Study area

Greater Bangalore is the administrative, cultural, commercial, industrial and knowledge capital of the state of Karnataka, India currently with a population of about 7 million and area of 741 sq. km. and lies between the latitude 12°39′00″ to 13°13′00″ N and longitude 77°22′00″ to 77°52′00″ E (Fig. 1). It is situated at an altitude of 920 m above the sea level where as winter temperature ranges from 12 to 25 °C, while summer temperature ranges from 18 to 38 °C. Mean annual precipitation is 880 mm [43–45]. Bangalore has grown spatially more than ten times (~69–741 km^2) since 1949.

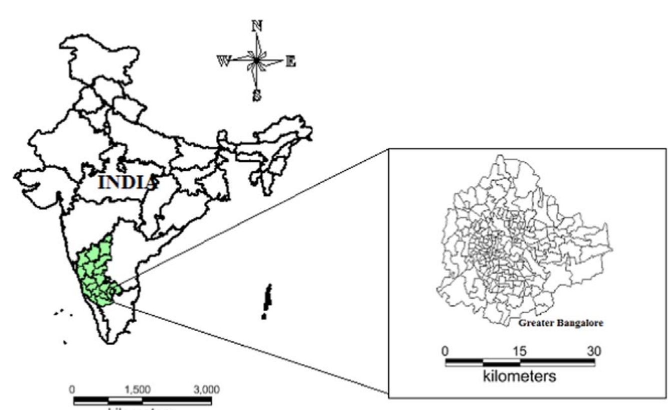

Fig. 1. Study area -Greater Bangalore.

Greater Bangalore is identified as Country's ‘Silicon Valley’, is the fifth metropolis city in India [46]. Bangalore city administrative jurisdiction was redefined in the year 2006 by merging the existing area of Bangalore city spatial limits with 8 neighbouring Urban Local Bodies (ULBs) and 111 Villages of Bangalore Urban District. Bangalore comprises of 198 administrative wards with diverse economic and social background families [47]. Bangalore city population has increased enormously from 5.7 million (in 2001) (Census, 2001) to 9.6 million (in 2016), accounting for 46.68% growth in a decade (due to spatial expansion of the city). Population density has increased from as 7778 (in 2001) to 12,955 (in 2011) persons per sq. km with vertical growth in many pockets. The Bangalore city grew rapidly during last four decades due to unplanned urbanization and has now become one among the fastest growing global cities.

Quantum of Municipal Solid Waste (MSW) has increased from 650 t per day - tpd (1988) to 1450 tpd (2000) and 3000 − 3600 tpd (2012) due to the increase in population with the expansion of spatial extent [45]. The daily collection is estimated at 3600 tpd with a per capita generation from 0.16 kg/d (1988) to 0.58 kg/d (2009). However, it is found, in other metro cities, Mumbai 0.45 kg/capita/d, Delhi 0.57 kg/capita/day, Kolkata 0.58 kg/capita/day, Chennai 0.62 kg/capita/day, Hyderabad 0.57 kg/capita/day (CPCB, 2004). Tables 2 and 3 list composition during different time period and physical composition at different levels. Among which, residence (household waste) is the foremost contributor to the total waste stream with a high proportion of biodegradable waste i.e., 72%. Whereas Kolkata household waste accounts 34.20% [48]. Presently, a quasi-centralized collection system is employed in Bangalore and the waste collection system from households (HH) closely follows the Municipal solid waste (handling and management) MSW (H & M) Rules 2000, employing door-to-door collection. In most of residential area the provision of dustbin is removed to avoid the multiple handling of waste [49,50]. The city has been facing severe shortage of landfills to dump garbage due to unplanned urbanization. Bruhat Bangalore Mahanagara Palike (BBMP) is responsible for management of solid waste.

During the early stages, a large part of the city wastes was sent to a compost plant situated outside the city limits KCDC (Karnataka Compost Development Corporation). In 1988, the city was producing 650 tpd, among this about 100 tpd of market wastes were taken back for direct application on the land and another 150 tpd was handled by KCDC. A large segment of decomposable was ‘open dumped’ along the various arterial roads at outskirts of the city [51]. This trend of open dumping had continued beyond 2000. Today as the quantum of wastes has increased drastically; most wastes are being openly dumped at about 60 known dumping sites and many unrecorded sites. Composting accounts for 3.14%, but with increase in urban solid waste, the number of compost plants has not increased. Among these, more than 35 sites possess a mixture of domestic and industrial waste [52]. This highlights that the existing solid waste treatment methods in the city are neither efficient nor well-organized.

3.2. Method

Assessment of the spatial patterns in GHG emissions due to solid waste generated in the municipality involved i) primary survey of sample household chosen randomly through the pretested and validated structured questionnaire and ii) compilation of ward-wise waste generation and composition data from the government agencies.

The survey at local levels (at ward levels – administrative unit to manage solid waste) helps to identify the problems and aid in evolving appropriate strategies for management of solid waste including the planning of household waste treatment options and its infrastructure.

3.3. Data collection

The structured questionnaire was designed to elicit information related to community attitude towards waste management behaviours and socioeconomic factors. The questionnaire was pretested through a sample survey of about 60 households before taking up large scale survey. Multistage, stratified random survey of urban residences was conducted covering 1967 households in this study. These households represent heterogeneous population belonging to different income, education, and social aspects. Spatial distribution of 1967 households in 8 zones (N: North, NE: North East, E: East, SE: South East, S: South, SW: South West, W: West and NW: North West) covering 138 wards is shown in Fig. 2. The survey considered parameters such as waste generation quantity, waste collection, time, frequency, number of persons involved in waste collection, collection done, size of bin, distance of the bin from house, bin clearance time, transportation of waste, landfill site, distance of transportation of waste and socioeconomic parameters includes income, household size, employment status, education level of the head of the family. About 1916 households responded to the quantity of solid waste generation per day.

3.4. Analysis method

Simple statistical analysis was done to assess the relationship between solid waste generation and socio-economic factors. Spatial distribution of houses and CO_2 equivalent emission from the wards of Bangalore were generated using GIS software MapInfo 7.5. In addition, the per capita generation rate was estimated using Eq. (1) and total quantity of waste is computed using Eq. (2).

Table 2
Composition of MSW generation in Bangalore.

Components	Composition (% by weight)			
	All over Bangalore, 1988	All over Bangalore. 2000	IISc, residential area. 2001	All over Bangalore
Fermentable	65	72	72.5	60
Paper	8	11	18	12
Miscellaneous	12	1.9		1
Glass	6	1.4		4
Polythene/plastics	6	6.2	9.5	14
Metals	3	1		1
Dust and sweepings		6.5		
Source	Rajabapaiah [51].	TIDE [50]	Satish kumar et al., 2001	BMP

Table 3
Physical composition of MSW in Bangalore.
Source: TIDE, [50]; Ramachandra, [1].

Waste type	Composition						
	Domestic	Markets	Hotel and eatery	Trade and commercial	Slums	Street sweeping and Parks	All sources
Fermentable	71.5	90	76	15.6	29.9	90	72
Paper and cardboard	8.39	3	17	56.4	2.49	2	11.6
Cloth, rubber, PVC, leather	1.39		0.33	3.95	0.54	0	1.01
Glass	2.29		0.23	0.65	8.43	0	1.43
Polythene/plastics	6.94	7	2	16.6	1.72	3	6.23
Metals	0.29		0.26	0.38	0.23	0	0.23
Dust and sweeping	8.06		4	8.17	56.7	5	6.53

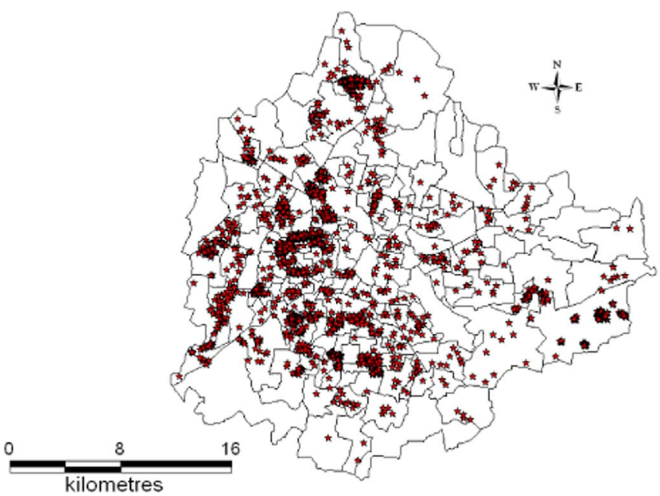

Fig. 2. Spatial Distribution of Residential Houses in the Surveyed Area.

$$\text{Generation rate(gram/capita/day)} = \text{Quantity of household waste (gram/day)/Population} \quad (1)$$

$$\text{Total quantity of waste (gram/day)} = \text{Generation rate (gram/capita/day)*ward population} \quad (2)$$

Mismanagement of solid waste rich in organic components emits greenhouse gases (GHG) such as Carbon Dioxide (CO_2), Methane (CH_4). The overall carbon footprint is calculated in terms of CO_2 equivalent emissions. The GWPs for the relevant greenhouse gases used were: CO_2 1, CH_4 23, which are used to convert emission of different gases. CO_2 equivalent emission from the solid waste is quantified by using Eq. (3).

$$CO_2\text{equivalent emission} = (W*EF_{CO2}) + (W*EF_{CH4}*GWP_{CH4}) \quad (3)$$

Where, W is organic waste (gram/day); EF is the emission factor (0.016 Gg/Gg of waste for methane, which is equal to the EF obtained from MTM reported from landfills of Delhi (Kumar et al., 2004b) and lower than the value reported from Chennai landfill site (Jha et al., 2008) and 2.25 Gg/Gg of waste for carbon dioxide), GWP_{CH4} is Global warming potential is 23 for CH_4.

Table 4
Waste generation (g/capita/day).

	Mean	Skewness	Std Error
Organic	74.09 ± 34.94	0.72	0.81
Paper	19.18 ± 22.22	2.88	0.65
Metal	10.66 ± 11.87	1.94	0.71
Glass	6.8 ± 5.01	0.69	0.39
Others	4.53 ± 1.74	5.11	0.04

Table 5
Percentage of composition of waste from surveyed area.

Composition of waste	Percentage of waste composition
Organic	81.96
Paper	12.69
Metal	1.67
Glass	0.65
Others	3.02

4. Results

4.1. Analysis of quantity of waste generation

Assessment of waste generation was done through quantification of waste generated at household per day. The total waste generation was 772.216 kg per day, surveyed across 8434 individuals. Table 4 lists the per capita waste generation composition along with descriptive statistics. Organic fraction in municipal solid waste based on the sample household's data is about 74.09 ± 34.94 g/person/day whereas in Delhi about 0.500 kg/capita/d was generated. Table 5 provides the waste composition, which reveals that organic fraction constitute the major share (81.96%) followed by paper (12.69%).

Zone wise analysis indicates the variability of waste generated in each zone given in Table 6. The few notable factors which are responsible for the variations are change in the food habits, affluence, income and change in lifestyle. The average organic waste ranges from 66.24 ± 36.77 g/person/day (South East) to 78.84 ± 33.02 g/person/day (East) and inorganic waste contributes about 24.71 g/person/day (South, North West) to 31.13 ± 34.19 g/person/day (East). The physical composition of waste from households is depicted in Fig. 3. The organic fraction (kitchen) was the largest component which accounts 82% of the total, paper waste is 13% next to kitchen waste. Earlier studies have reported [53] a relatively lower value, indicating the increase of organic fraction from 72% (in 2005) to about 82%. Higher proportion of organic fraction in municipal solid waste and open dumping in absence of appropriate treatment leads to the release of GHG. This necessitates quantification of GHG and appropriate measures to mitigate GHG emissions through the treatment of organic fractions in MSW. Studies done in the neighbouring developing countries, show 66% [38] and 90% of Organic waste [54]. The spatial distribution of per capita waste generation per day (Fig. 4) indicates that majority of households i.e., 926 households generates 50–100 g of waste. 497 households generate 100–150 g followed by 214 households generates less than 50 g and 155 households generates 150–200 g. Table 7 compares the physical composition of city wise household waste. The results reveal that Bangalore has a higher percentage of organic fractions in municipal solid waste compared to other cities. The most apt way to treat the waste rich in organic fractions is decentralised systems of either bio-methanation or composting.

Table 6
Statistical analysis of waste generation (g/capita/day) across the zone.

Zones	Parameters	Mean	Minimum	Maximum	SD	Skewness	Std Error
East	Organic	78.84	4.67	187.50	33.02	0.55	2.03
	Inorganic	31.13	0.63	173.33	34.19	2.25	2.73
NE	Organic	78.70	12.50	150.00	31.60	0.27	6.20
	Inorganic	29.98	2.50	125.00	33.35	1.78	8.34
North	Organic	71.76	6.67	250.00	35.33	0.87	2.07
	Inorganic	24.82	1.00	186.67	29.07	2.63	2.09
NW	Organic	69.14	10.00	200.00	32.51	0.87	2.09
	Inorganic	24.71	0.83	200.00	30.88	2.76	2.40
SE	Organic	66.24	12.00	166.67	36.77	0.73	5.61
	Inorganic	29.70	2.00	166.67	39.85	2.28	7.67
South	Organic	74.22	12.00	250.00	37.39	0.88	2.20
	Inorganic	24.71	1.25	137.50	26.36	2.01	1.93
SW	Organic	74.38	11.11	175.00	34.22	0.48	2.17
	Inorganic	26.56	1.25	187.50	29.85	2.26	2.42
West	Organic	75.74	4.17	222.22	35.52	0.70	1.69
	Inorganic	27.37	1.00	208.33	32.66	2.28	1.88

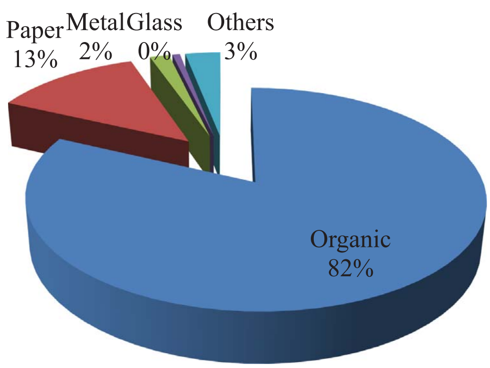

Fig. 3. Composition of household waste.

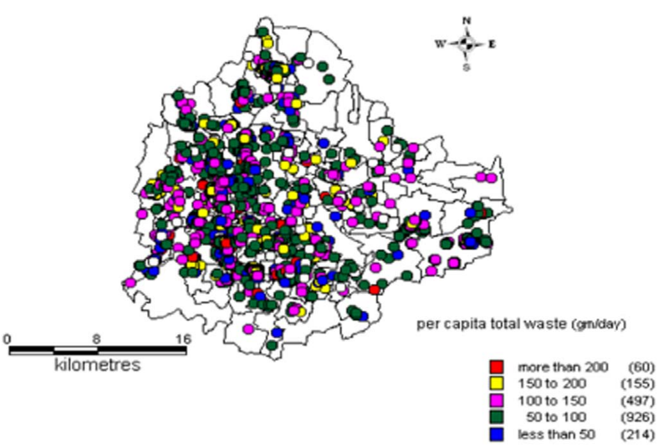

Fig. 4. Spatial distribution of per capita waste generation of sample.

4.2. SWM at household level in Greater Bangalore

The collection, transportation and disposal of MSW are significant aspects of waste management. Waste collection (Fig. 5a) is done either through doo-to-door collection systems (64.57%) or through community bins (35.43%). Wards in Bangalore has both community bin and door to door collection system (ex; Bellandru, Varthur, Yelahanka Satellite Town, Vidyaranyapura and Arekere) but majority of the wards (Sunkenahalli, Kormangala, Malleshwaram) the households were served with door-to-door collection system (Fig. 5b). In Bangalore city, the waste collection is done by the Bangalore Mahanagara Palike (BMP) or outsourced agencies. Swachha Bangalore a novel initiative launched in 2003 by BMP (Bangalore Mahanagara Palike) and Bangalore Agenda Task Force to manage the waste effectively. Under this initiative, door to door collection of waste, segregation at source were introduced in model wards of Bangalore.

In majority of wards (64%) the waste is collected in the morning (6.00 a.m. to 11.30 a.m.) and only in 21 households (Fig. 6a) from surveyed area the waste is collected in evening mainly in the part of Yelahanka Satellite Town and Herohalli and in 0.36% households (Fig. 6b), waste is collected in the afternoon.

The frequency of collection of waste from door-to-door given in Fig. 7a show that about 46% of the area the waste is being collected daily (ex; Sampangiram Nagar at centre of the city, Raja Rajeshwari, Malleshwaram, Rajajinagar, Jayanagar, Bellendur). 12% of wards (ex. Varthur, Hagadur, Kadugodi, Singasandra) the waste is collected weekly four times, thrice a week in 2% wards and twice a week in about 1% of wards depending on the area and in about 3% of surveyed area the waste is collected once in a week and remaining 1% of the population did not respond to the question (Fig. 7b).

Number of persons involved in collection of waste from door to door was also surveyed and is represented in Fig. 8a and b respectively. In most of the wards two persons were involved in collecting the waste (39%) followed by one person (20% of the total area), illustrated in Fig. 8a. 35% area have the facility of community bin and remaining 37

Table 7
Comparison of Household waste generation in different cities (as percentage).

City	Organic	Paper	Plastics	Metal	Glass	Textile	Wood	Others
Bangalore(India)	84	12	–	1	1	–	–	2
Bejing (China)	69.3	10.3	9.8	0.8	0.6	1.3	2.7	–
Cape Haitian (Republic of Haitian)	65.5	9.0	9.2	2.6	5.8	–	–	7.9
Chittagong (Bangladesh)	62	3	2	–	5	1	3	–

References: Qu et al. [34]; Philippe and Culot [37]; Sujauddin et al. [38].

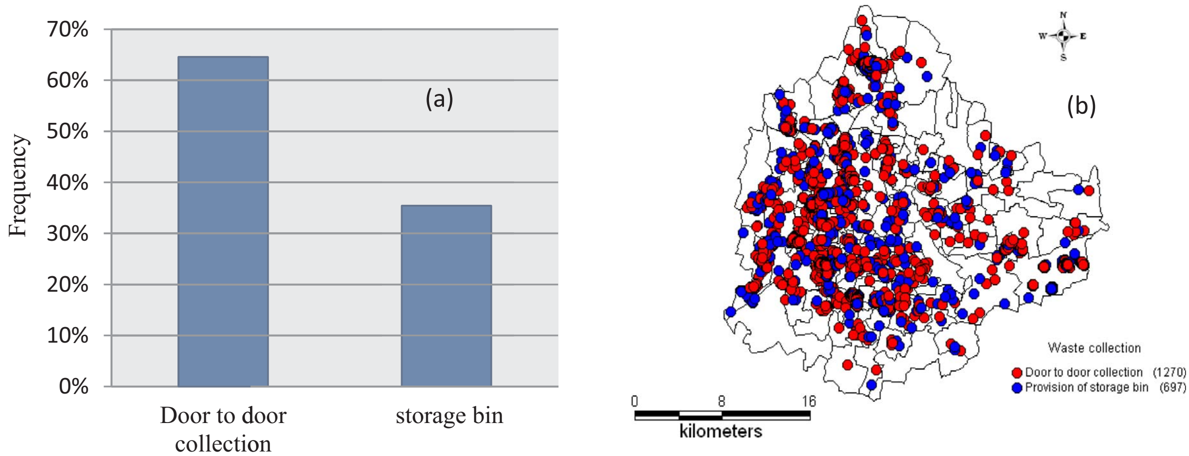

Fig. 5. Waste collection.

households did not respond to the question (Fig. 8b). Municipality (90%) is engaged in waste collection from households to final dumping sites in most parts of the city, whereas only in the few areas, private contractor and NGO's (Swabhimana, Swachha Bangalore, Shuchi Mitras) represents 8% and 2% respectively to collect the waste from household (Fig. 9a and b).

The analysis of distance of community bin from the households in the surveyed (Fig. 10a and b) show that the dustbin is within 100 m in 23% of the surveyed area, while in 11% area, bins is in the range of 100–500 m away from houses and 10 households did not respond to the question and rest of the houses served with the door to door collection system. Fig. 11a and b reveals the bin size in surveyed area. There are two types of storage bins; stationary bin and hauled bin. Depending on the local culture, tradition and attitudes towards waste, the bins are allocated. Majority of the wards the bin size is 1 m^3 accounts 13.5% whereas in 7% area has less than 1 m^3 bin, 196 households did not answer which might be due to the absence of community bin and about 64% of households have the facility of door to door collection system of waste.

The segregation of waste carried out at the household level is given in Fig. 12a and b respectively, which highlights that about 78.34% households do not segregate the waste before dumping into dustbin. This shows lack of awareness and general attitude of public towards segregation of solid waste. 21.66% segregate the waste into organic and inorganic waste or dry and wet waste in the south part of Bangalore (ex. Varthur, Dodda Nekundi, H B R layout, Basavanagudi, etc.). Street bin is cleared of litter by the municipality in the locality show that in majority of wards the bin is cleared weekly which accounts 45% while in other wards bin is cleared daily and 2/3 days once were 42% and 13% respectively (Fig. 13a and b).

Finally transportation of waste plays an important role in waste management of the city. The transportation of waste and distance of transportation of waste was also captured in the survey and is as illustrated in Fig. 14a, b, 15a and b respectively. A large percentage of sample households (85%) do not know about the transportation of waste (final dumping site), only 205 households from the surveyed area, were aware about the transportation of waste. Among 205 households, 9% of the residential stated that the waste is transported between the range of 10–100 km where as 4% stated it is transported less than 10 km and 1% stated that it is transported greater than 100 km and 28 households did not respond to the question. Fig. 16a and b reveal that of 71% of the region has no provision of landfill site, while landfill exists only in 28% area mainly in the north-east and west part of the outskirts in the Bangalore.

4.3. Survey of socioeconomic factors

A number of socioeconomic parameters such as household size, income, employment status and education status influence the quantum of solid waste generated and management of organic waste. Table 8 shows the frequency, percentage and cumulative percentage of the socioeconomic factors of households. It indicates the average household size is 4.5 ± 1.74 persons/hh. Majority of the households have four (45.86%) persons, followed by 5 persons (19.2%), 3 persons (15%), 6 persons (13.9%), greater than 6 (5.4%), etc. The education and employment status mainly influence the food habits, materials consumed and waste generation. Graduates constitute 36.71% followed by high school educated (24.66%). The average monthly income INR 35,563.63 ± 77,851, similar to earlier studies [3,39,55].

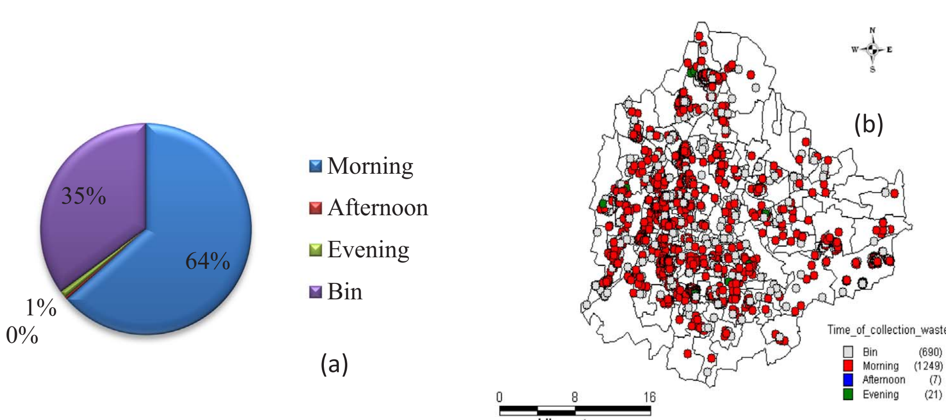

Fig. 6. Time of waste collection.

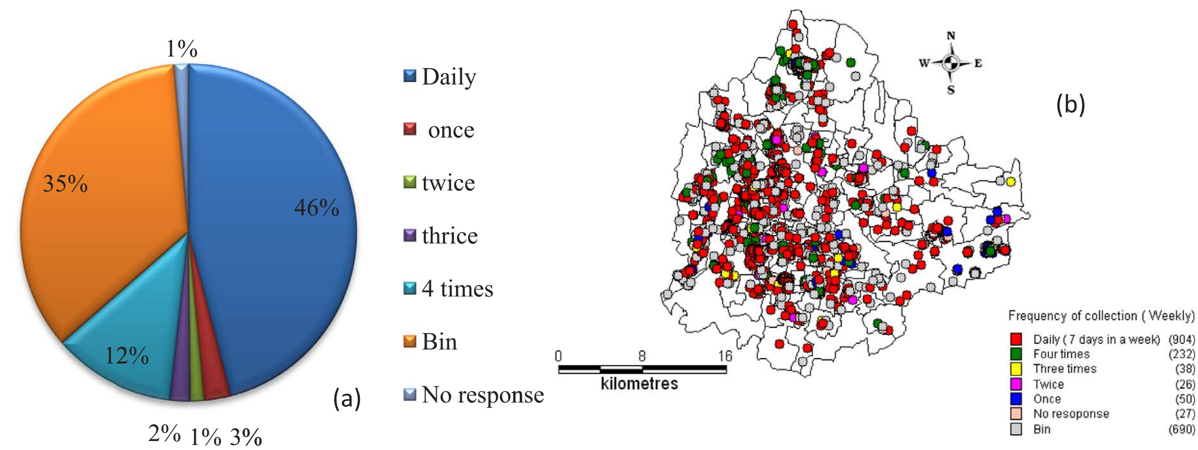

Fig. 7. Frequency of collection.

4.4. Relationship between the quantity of household solid waste generated and socioeconomic factors

Family size is an important factor in the household waste generation and Fig. 17(a) shows the household size was negatively related to the daily per capita waste generation. As the family size increases, the per capita waste generation decrease gradually similar to the earlier reports [56,57] indicating smaller household size produced more per capita waste than the larger household size. The probable relationship of per capita solid waste generation with household size is given in Eq. (4).

$$PCSW = 0.258516 - 0.0200168*HH \text{ (at } p < 0.005,\ R: 0.8) \quad (4)$$

Where, PCSW: per capita solid waste generated per day and HH: household size

The household income is classified into four categories, less than 100,000, 100,000–500,000, 500,000–1,000,000 and greater than 1,000,000. Fig. 17(b) indicate that family with an income > 100,000 produces more per capita waste compared to the other families. The relationship between family income and per capita waste quantity was found to be significant i.e., as the family income increases the consumption pattern and purchase trend increases which in turn leads generation of more solid waste quantity, comparable to the earlier reports [34,55] highlighting that family income is positively related to the waste generation rate. The probable relationship is given by Eq. (5).

$$PCSW = 0.244 + 0.00096*\text{Family income (at } p < 0.005,\ R: 0.88) \quad (5)$$

Where, PCSW: per capita solid waste generated per day, Family income ranges from 1,2..10; 1: annual income < 1,000,00; 2: annual income of 1,000,00–2,000,00 ….. 10: 8,000,00 to 1,000,000

The education levels of the family were not found to be significantly related with per capita waste generation is illustrated in Fig. 17(c). Families with the education level of masters produces more per capita waste than the families with members consisting of higher levels of education above Post graduation (persons with PhD). In this study the employment status is not significantly related to the waste generation Fig. 17(d). The head of the family who are in the business produces more waste than the families who are working in the other sectors. The total waste generation from the household increases as the income increases is depicted in Fig. 17(e). The probable relationship of per capita solid waste generated with education status is given by Eq. (6).

$$PCSW = 0.267 + 0.002613*EDU \text{ (at } p < 0.005,\ R: 0.68) \quad (6)$$

Where, PCSW: per capita solid waste generated per day and EDU: Education status of the family head (Middle school or lower: 2, High school: 3, Technical school: 4, University: 6, Masters: 8, Ph.D: 10)

Regression of multiple independent variables (HH: Household size; EDU: Education level; FAI: Family's annual income with dependent variable PCSW (per capita solid waste generated) is given by Eq. (7).

$$PCSW = 0.2551 - 0.0181*HH + 0.002081*EDU + 0.00085 *\text{Family Income (at } p < 0.005,\ R: 0.56) \quad (7)$$

Table 9 lists the descriptive statistics on the physical composition of household waste with different socioeconomic groups. This indicates that organic waste is the prominent component in the solid waste composition in all the socioeconomic groups. It is also evident that as the income level increases the organic waste composition decreases with the increase in the proportion of paper, metal, glass and others. The organic waste generated from household varies from 80% to 82% in the surveyed area. Among them, the high income family group

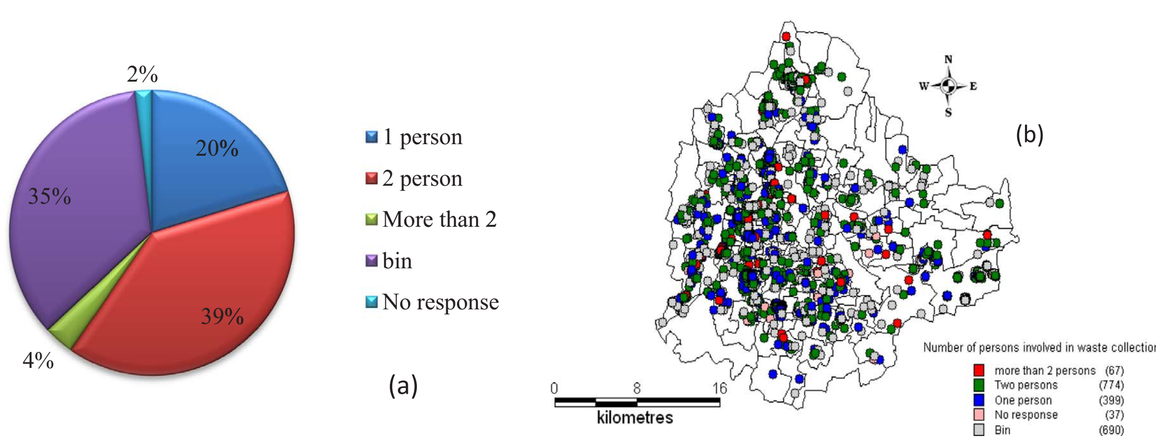

Fig. 8. Persons involved in door to door collection.

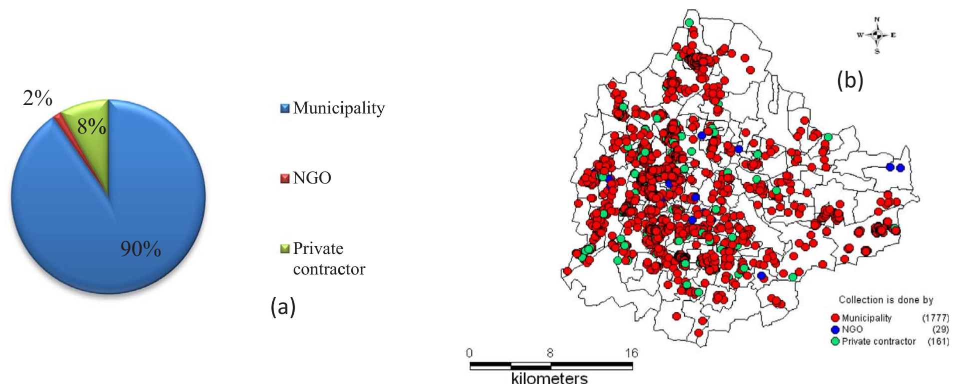

Fig. 9. Collection of waste.

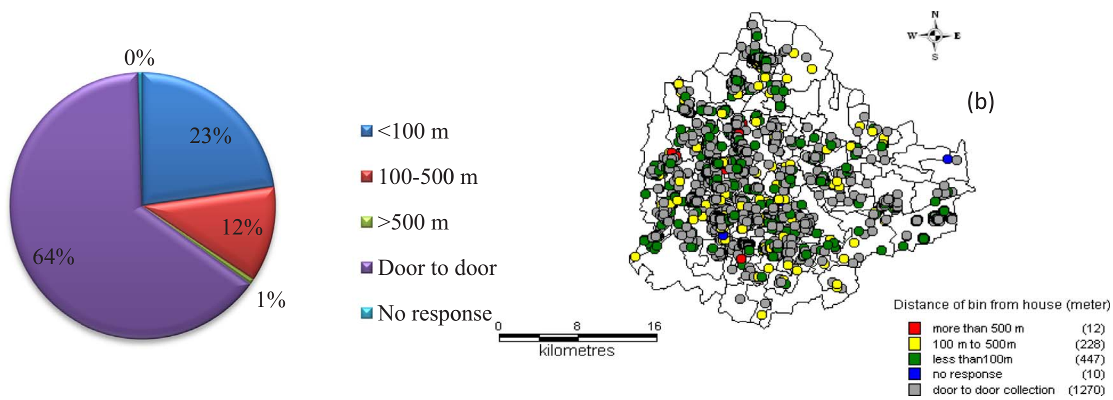

Fig. 10. Distance of the bin from house (in meter).

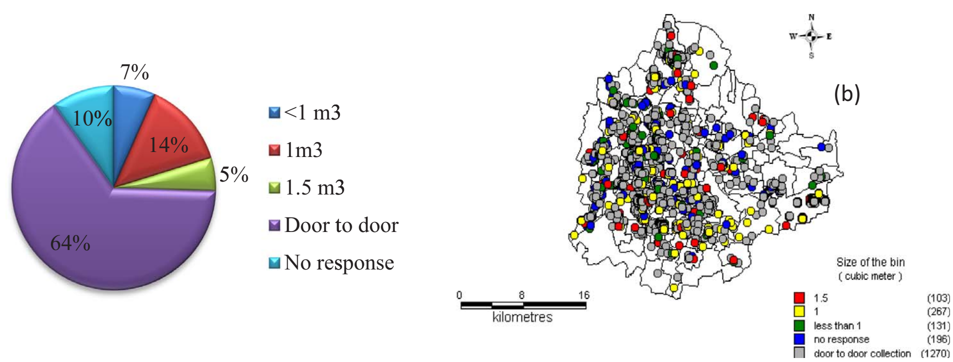

Fig. 11. Size of the bin.

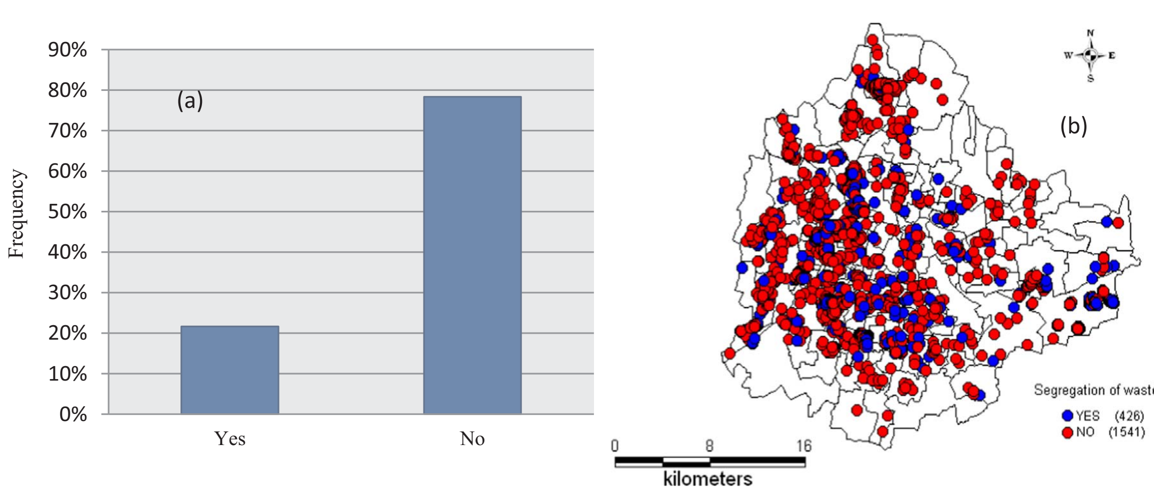

Fig. 12. Segregation of waste.

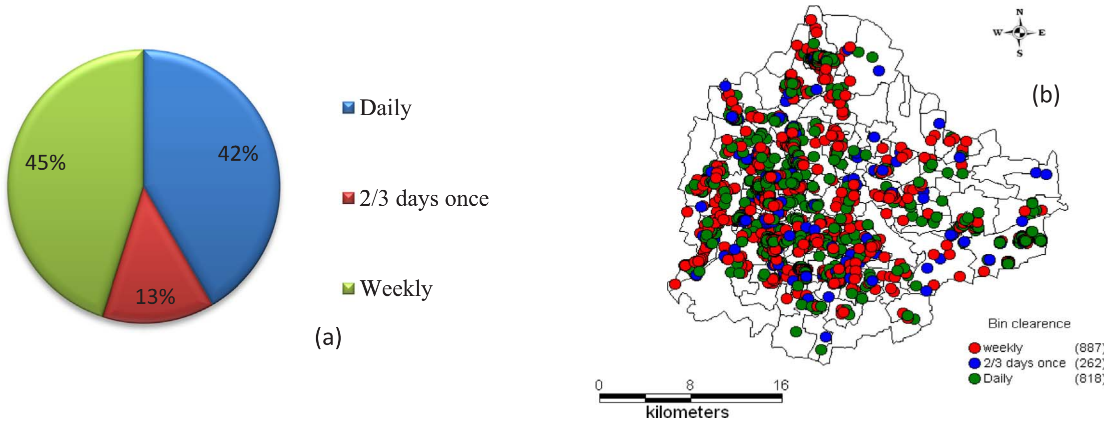

Fig. 13. Bin clearance.

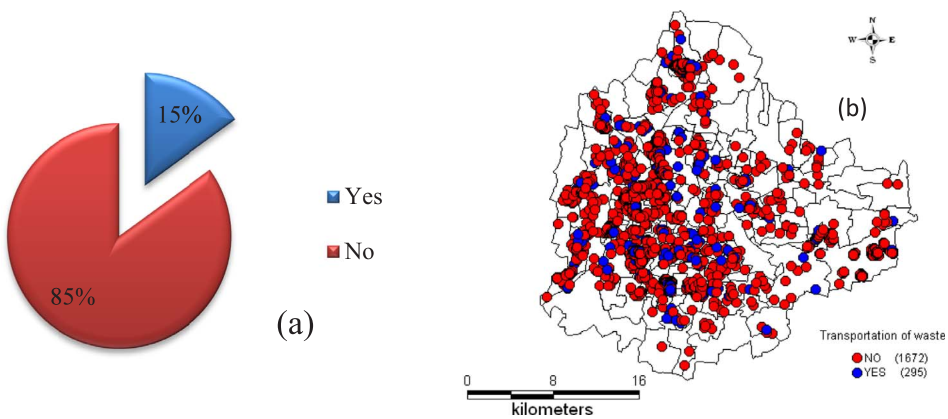

Fig. 14. Transportation of waste.

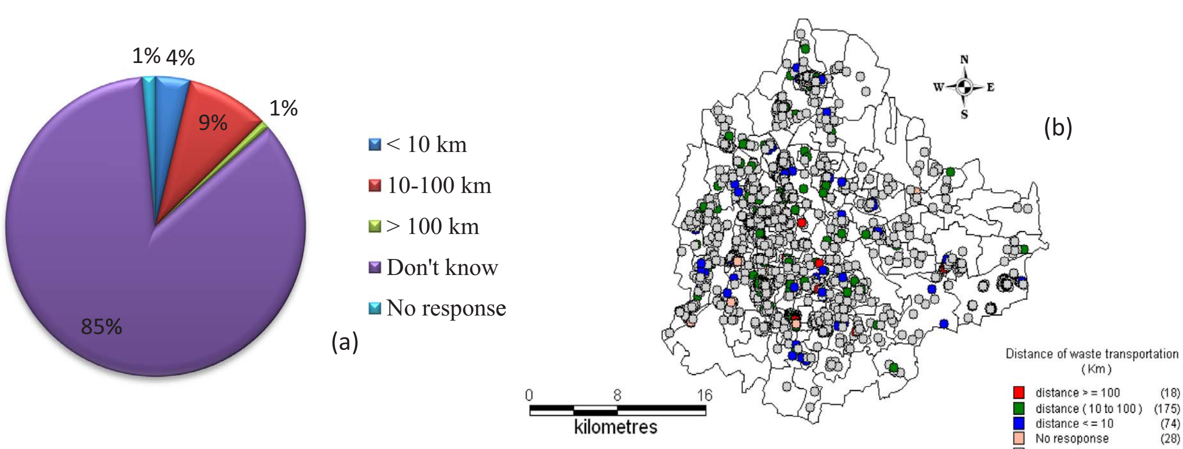

Fig. 15. Distance of the waste transportation.

(> 1,000,000) produces the lowest (80.31%) organic waste and low income family group (< 100,000) produces the highest organic waste (85.52%). The organic waste generation was found to be increasing from high income family group to low income family group. The opposite trend is observed for the paper, glass and others. In case of metal, the lowest percentage is 1.20% in low income family group (< 100000) and highest percentage is 1.73% in high income family group (> 1,000,000) but the family group with the income of (500,000–1,000,000) produces less percentage compared to the family group with the income of (100000–500000). For glass, the lowest percentage is 0.52% in low income family group (< 100000) and highest percentage is 0.63% in high income family group (> 1,000,000) but the family group with the income of (500,000–1,000,000) and (100,000–500,000) contribute same percentage 0.58% of glass, comparable to [39]

4.5. Carbon dioxide emissions from household

Mismanaged municipal solid waste is the significant contributor to the greenhouse gases such as methane and carbon dioxide in the atmosphere. CO_2 equivalent emission from organic waste generated at household is calculated by using the Eq. (3). According to this study, the total organic waste generated from surveyed houses was 231.01tons/year and total emission is about 604.80 t/year. Table 10 lists zone wise CO_2 equivalent emission (Gg/year) from solid waste generated in Bangalore. The Mean ward wise CO_2 emission varies from 2.59 (North) to

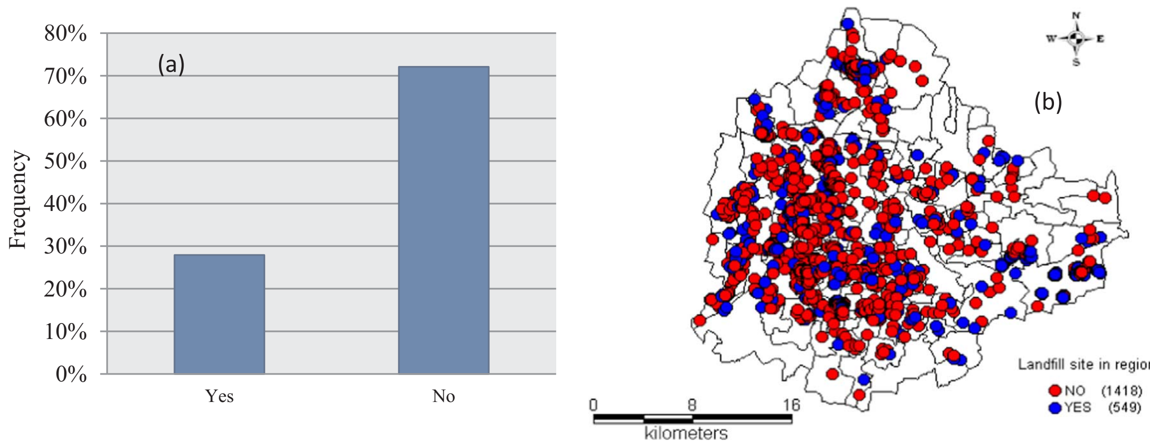

Fig. 16. Landfill site in the region.

Table 8
Frequency, Percentage and Cumulative Percentage of the socioeconomic factors.

Variables name	Frequency	%	Cumulative %
1. **Family size**			
2	20	1.02	1.02
3	286	14.54	15.56
4	902	45.86	61.41
5	378	19.22	80.63
6	146	7.42	88.05
More than 6	128	6.51	94.56
No response	107	5.44	100.00
2. **Education status**			
Middle school or lower	134	6.81	6.81
High school	485	24.66	31.47
Technical school	278	14.13	45.60
Universities	722	36.71	82.31
Masters	269	13.68	95.98
PhD	79	4.02	100.00
3. **Employment status**			
Government institution	460	23.39	23.39
School/hospital/research or design institute	83	4.22	27.61
Foreign corporation	113	5.74	33.35
Local company	235	11.95	45.30
State corporation	67	3.41	48.70
Business institute	391	19.88	68.58
Others	587	29.84	98.42
No response	31	1.58	100.00
4. **Monthly income**			
< 10,000	509	25.88	25.88
10,000–50,000	1192	60.60	86.48
50,000–100,000	183	9.30	95.78
> 100,000	83	4.22	100.00

3.23 Gg/year (South West). The CO_2 equivalent emission from solid waste generated at household (kg/capita/day) is depicted in Table 11. It reveals that the average CO_2 equivalent emission is low in South East (0.17 kg/capita/day) and highest in East and North East zones (0.21 kg/capita/day). Fig. 18 illustrates the spatial distribution of CO_2 equivalent emission from solid waste. Fig. 19 reveals the per capita CO_2 equivalent emission from households in the surveyed area. 926 households emit 50–100 kg/person/year, 624 households emit less than 50 kg/person/year, 247 households emits 100–150 kg/person/year and only 46 households emits more than 150 kg/person /year. Fig. 20 highlights GHG emissions from all the wards of Bangalore. The average ward-wise CO_2 equivalent emission is 2.93 ± 0.91Gg/year. 47 wards emit in the range of 3 to 3.5Gg/year while 46 wards emit more than 3.5 Gg/year. 45 wards emit in the range of 2–2.5 Gg/year, 39 wards 2.5–3 Gg/year and 18 wards emits in the range of 1.5–2 Gg/year. Remaining 7 wards emits less than 1.5 Gg/year.

5. Policy recommendation to mitigation of GHG emissions

Scope for mitigation of GHG emission is through the recovery and conversion of organic component (which constitute 70–82%) to energy or compost. Policy interventions for the adoption of integrated solid waste management (ISWM) through the incorporation of the waste management hierarchy considering direct impacts (transportation, collection, treatment and disposal of waste) and indirect impacts (use of waste materials and energy outside the waste management system) would reduce the carbon footprint due to mismanagement of waste [58]. In this context, Government of India has formulated Solid Waste Management Rule, 2016 [59], emphasising source segregation of organic fractions, treatment of organic fractions to either compost or manure, public awareness of segregation, etc., allow only the non-usable, non-recyclable, non-biodegradable, non-combustible and non-reactive inert waste and pre-processing rejects and residues from waste processing facilities to go to sanitary landfill and the sanitary landfill designed as per the specifications.

ISWM framework optimizes the existing systems and implements new waste management systems. In addition to climate concern, the recycling and energy recovery enriches the resource efficiency and reduce the environmental impacts from greenhouse gas emission. The strategy includes:

- Environmental awareness programme for citizens to segregate waste at source. The biodegradable organic waste brings a dominant component in MSW, treatment of organic fractions through appropriate technologies helps in the resource recovery while addressing its negative impact on the environment and potential economic benefits
- Segregation of waste at source (separate organic and inorganic - recyclable, reusable fractions);
- Incentive based segregation system: Door to door collection of waste with incentive based mechanism to enhance segregation at source: This entails (i) deploying appropriate mobile collection vans (for each locality) with an option to store segregated and unsegregated wastes, (ii) incentive of Rs 1 per kg of segregated organic waste and payment directly to the respective household account through bank transfer (iii) dis-incentive to unsegregated waste. Revenue generation through incentives would encourage many households to switch over to segregation.
- For large cities, ward-wise decentralised composting units should be setup to reduce the load of collection and transportation of MSW, which subsequently reduces the pressure exerted on the landfills.
- A waste stream with a high biodegradable organic content can be processed to produce high-quality compost which avoids land filling and enables the provision of manure to enrich soil. The

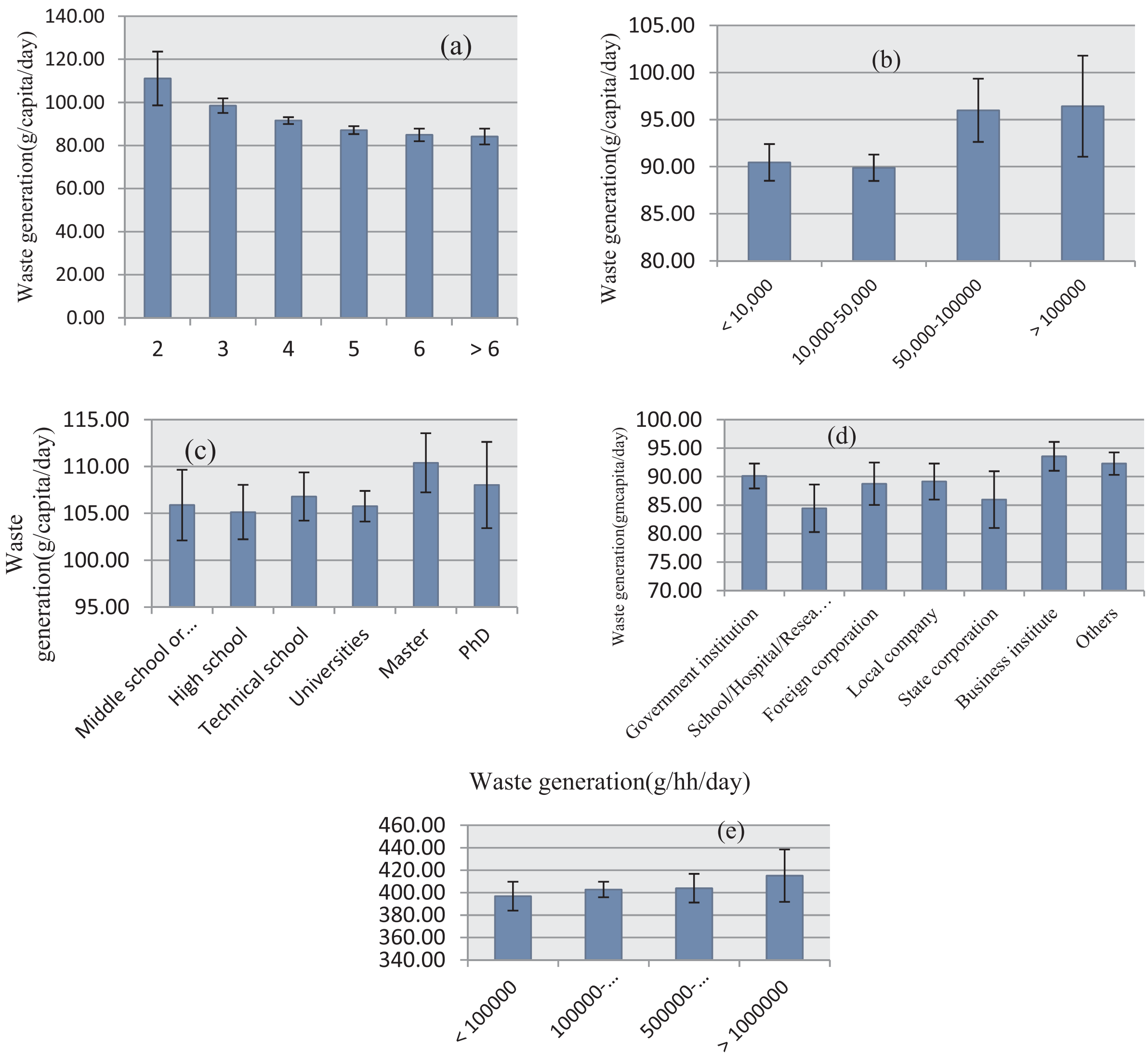

Fig. 17. Relationship of per capita waste generation with socioeconomic factors (a) effect of household size on per capita household waste generated; (b) effect of monthly on per capita household waste generated; (c) effect of educational level on per capita household waste generated; (d) effect of occupation on per capita household waste generated; (e) effect of annual income on total waste generated.

Table 9
Descriptive statistics of physical composition of household waste generated with different socioeconomic groups (as a percentage).

Annual income	Organic	Paper	Metal	Glass	Others
< 100,000	85.52	11.62	1.20	0.52	1.14
100,000–500,000	84.09	11.35	1.51	0.58	2.47
500,000–1,000,000	82.99	13.50	1.22	0.58	1.72
> 1,000,000	80.31	14.72	1.73	0.63	2.61

Table 10
CO_2 equivalent emission from solid waste in Bangalore (Gg/year) across the zone.

Zone	Mean	Min	Max	Sum	SD
East	3.11	0.49	5.37	62.21	1.21
North East	2.89	1.66	4.70	57.87	0.80
North	2.59	0.60	5.58	54.41	1.01
North West	3.05	1.99	3.75	70.15	0.50
South East	2.72	0.59	6.25	32.62	1.47
South	2.62	1.01	4.69	83.93	0.80
South West	3.23	2.00	6.25	96.90	0.82
West	3.10	1.76	4.84	102.18	0.78

Table 11
CO_2 equivalent emission from solid waste generated at household (kg/capita/day) across zone.

Zone	Mean	Sum	Minimum	Maximum	SD
East	0.21	54.49	0.01	0.49	0.09
North East	0.21	5.36	0.03	0.39	0.08
North	0.19	54.67	0.02	0.65	0.09
North West	0.18	43.81	0.03	0.52	0.09
South East	0.17	7.46	0.03	0.44	0.10
South	0.19	56.15	0.03	0.65	0.10
South West	0.19	48.30	0.03	0.46	0.09
West	0.20	87.25	0.01	0.58	0.09

biodegradable fraction has the appropriate moisture content for composting.

- Promotion of recycling or reuse of segregated material reduces the quantity of waste and the burden on landfills, and provides raw materials for manufacturers.
- Improved storage containers for the storage of biodegradable / wet wastes.
- Setting up transfer stations taking in to account local situations to improve the efficiency of waste collection, especially in narrow

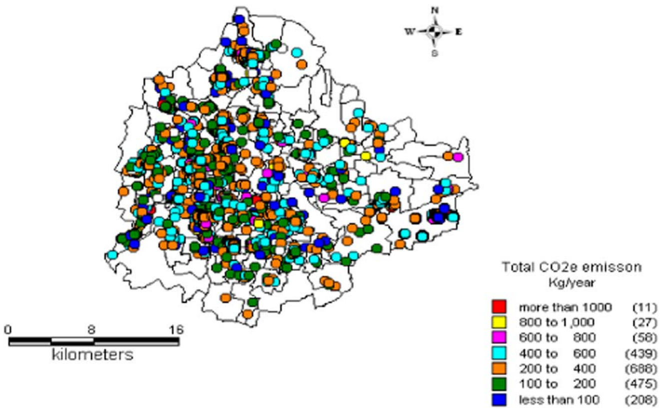

Fig. 18. CO_2 equivalent emission from household solid waste generated.

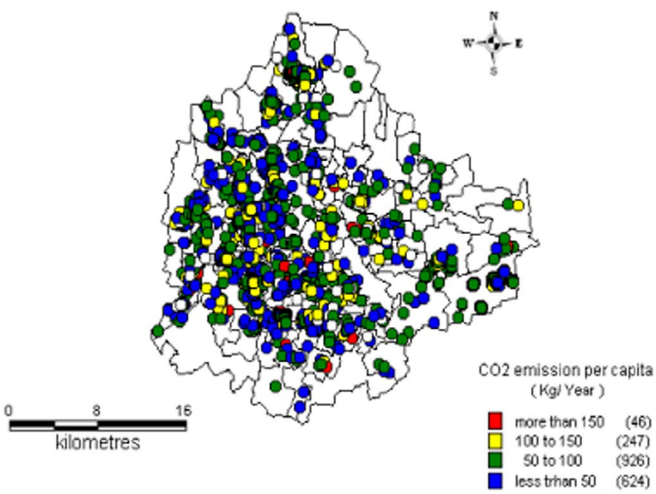

Fig. 19. Per capita CO_2 equivalent emission from household solid waste generated.

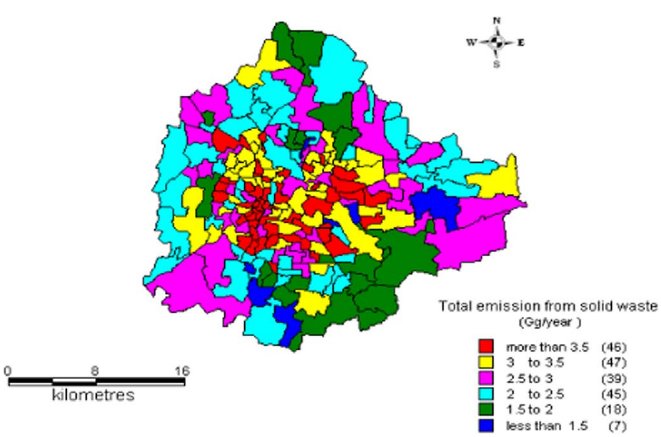

Fig. 20. ward wise GHG (CO_2 equivalent) emission from Bangalore city.

roads and slums, this will ensure the proper handling of wastes and the reduction of transportation costs.

- Primary collection of waste stored in various locations on a daily basis through active public participation.
- Improved collection vehicle design to increase capacity and ergonomic efficiency.
- A helpline to tackle various issues such as road sweeping, open dump, open burning, garbage collection, etc.
- Garbage tax to be levied to the large and small generators for the disposal of wastes.
- Adequate training to all the levels of staff engaged in solid waste management to handle respective functional aspects (collection, generation, storage, segregation of waste, etc.).
- Adoption of technological solutions such as bio-gas recovery, composting, etc. for affecting improved recovery and disposal of waste.
- Adoption of GIS (Geographic Information System) with GPS (Global Positioning System) would streamline collection of waste garbage and improves efficiency.
- Constitution of citizen forum in each corporation ward involving local people, NGO's and concerned authorities to ensure close monitoring and supervision of waste management practices regularly.
- Taking into account the bulk wastes to be handled every day, sanitary landfill sites have to be set up to dispose of the rejects after composting and landfilling.
- Regular monitoring of sanitary landfill sites involving local people in the team along with sanitary authorities.
- Administrative restructuring of the urban local bodies to discharge more efficiently specific responsibilities. This requires structural changes within the administration aimed at decentralizing authority and responsibilities. This also includes periodic meetings among the staff and between the executives and elected wing of the corporation.
- Encouraging the involvement of local NGO's in working on various environmental awareness programmes and areas related to waste management including educating the public about the importance and necessity of better waste management.

6. Conclusion

GHG emissions in the municipal waste sector are quantified based on the sampling of 1967 households in Greater Bangalore chosen through multistage, stratified random sampling. The outcome of the analysis showed the daily solid waste generation from 1967 residential households in surveyed area of Greater Bangalore was about 772.2 kg and the per capita of 91.01 ± 45.52 g/day. The analysis revealed that the organic fraction (82%) constitute a major portion of household wastes. The total organic waste is 632.92 ± 0.210 kg/day with the per capita organic waste generation of 74 ± 35 g/person/day. This emphasise the need for appropriate treatment option to minimise GHG emissions.

Most of the households (64%) in the study area have the facility of door to door collection of solid waste and about 78.34% of city population do not segregate the waste at source (household level). The decision makers should bring awareness among citizens and pourakarmikas (BMP staff) through capacity building workshops highlighting the importance of segregation at source level and promotion of recycling and reuse methods. This will reduce the quantity of waste and burden on landfills while ensuring the sustainability of natural resources. Further the study has revealed the relationship between waste generation and socioeconomic factors. The family income and family size are positively related and the education status is negatively related with per capita waste generation at household level. The average carbon dioxide equivalent emission from household is 307.50 ± 205.51 kg/year and per capita emission is 66.33 ± 36.61 kg/year. Further research is necessary to evaluate the seasonal variation in solid waste generation and composition as well as relationship between household waste generation and socioeconomic factors at household level during different time period. Environmentally sound solid waste management involves:

- Segregation of waste at source (separate organic and inorganic - recyclable, reusable fractions);
- Door to door collection of waste with incentive based mechanism to enhance segregation at source. Revenue generation would encourage many households to switch over to segregation;

- Collection trucks to have GPS (global positioning system) which would help in online tracking and also in reducing malpractices associated with waste management;
- Transparency in the administration though online availability of spatial information system, accessible to all including public;
- Eradicating waste mismanagement lobby - nexus of contractors-consultants-engineers. Successful elimination of the mismanagement lobby would help in solving the waste problem in any city. Only inert materials shall go to landfill locations;
- Setting up waste processing yards with decentralised treatment of organic fraction of waste in each locality (stop using parks and recreation spaces for this purpose);
- Encouraging youth to take up innovative waste treatment options (suitable to handle Indian waste- rich in organic fractions);
- Implementation of SWM 2016, GoI and penalising the city administrator in-charge of city waste for dereliction of duties in cases of mixed waste reaching the landfill site or littering of waste's in city open spaces.

The implementation of functional elements (such as segregation at source, storage, treatment of organic fractions, etc.) of solid waste management would aid in reducing GHG emissions and hence the changes in the climate.

Acknowledgement

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