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REGIONAL CASE STUDY

Physico-chemical characterization of municipal solid waste from Tricity region of Northern India: a case study

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Abstract An integrated solid waste management system is an effective method for controlling the huge volumes of solid waste generated in urban locales in India. The success of the integrated solid waste management system depends upon the amount and type generated from different sources for better facilitating of the appropriate management system. In this context, characterization studies are often performed on urban solid waste generated to enable suitable decision making for proper management of solid waste generated. The paper presents the characterization of urban solid wastes generated from the Tricity region of Chandigarh, Mohali and Panchkula in India. The present study characterizes the physical and chemical properties of the Municipal Solid Waste (MSW) generated in all the three study locations for different socio-economic groups. In general, the MSW generation from the Tricity of Chandigarh, Mohali and Panchkula account for approximately 680 tons per day (TPD) of solid waste (380 TPD in Chandigarh, 150 TPD in Mohali and 150 TPD in Panchkula). The characterization of the three cities indicates that MSW generated from all the three cities have high proportions of biodegradables [52% Chandigarh (CHD), 46.7% Mohali (MOH) and 42.6% Panchkula (PKL)] with inert fraction as (27% in CHD, 28.6% in MOH and 28.46% in PKL). The calorific value of the MSW generated varies from 1929 kcal/Kg for CHD, 1801 kcal/Kg for MOH and 1542 kcal/Kg for PKL with average moisture content of about 50% in CHD, 46% in MOH and 40% in PKL. Chemical characterization results of MSW reveal variation in elemental carbon with carbon fraction reported being 34.18% in CHD, 33.8% in MOH and 31.9% in PKL city. In the context of the characterization study, the paper also proposes suitable alternatives to the existing MSW management practices including composting, vermicomposting, setting up of a formal recycling unit and installation of bio-methanation plant along with the existing refuse derived fuel (RDF) plant as a comprehensive process for handling the municipal solid waste generated in the Tricity region.

Keywords Characterization of municipal solid waste · Refuse derived fuel · Moisture content · Calorific value · Biomethanation · Vermi-composting

Introduction

India's economy is expected to rise to 38% by the year 2026 [37, 56, 59] and as such the volume of the MSW generated is expected to increase manifold times [20, 30, 32, 42]. As per the latest report of Central Pollution Control Board of India (CPCB) the total amount of MSW generated is 1, 27,486 TPD of which 89,334 TPD (70%) is collected and 15,881 TPD (13%) is processed or treated [12]. In India, the per capita generation of solid waste varies from 0.15 kg in rural locations to 0.45 kg in urban areas [2, 28]. The state wise MSW generation in Indian cities is shown in Table 1. Proper management of MSW is a complex process which has been further affected due to reduced budgetary provisions available to the municipal authorities [19, 26, 42–48, 55]. As a consequence of this and existing prevalent practices and non-implementation of proper legislative guidelines, about 90% of the MSW

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Table 1 Municipal solid waste generation in India (State-wise); CPCB, 2015

S. no.	Name of the state/UT	Municipal solid waste MT/day (2009–2012)	S. no.	Name of the state/UT	Municipal solid waste MT/day (2009–2012)
1.	Andaman and Nicobar	50	18.	Lakshadweep	21
2.	Andhra Pradesh	11,500	19.	Maharashtra	19.204
3.	Arunachal Pradesh	93.802	20.	Manipur	112.9
4.	Assam	1146.28	21.	Meghalaya	284.6
5.	Bihar	1670	22.	Mizoram	4742
6.	Chandigarh	380	23.	Madhya Pradesh	4500
7.	Chhattisgarh	1167	24.	Nagaland	187.6
8.	Daman Diu and Dadra	41	25.	Orissa	2239.2
9.	Delhi	7384	26.	Puducherry	380
10.	Goa	193	27.	Punjab	2793.5
11.	Gujarat	7378.775	28.	Rajasthan	5037.3
12.	Haryana	536.85	29.	Sikkim	40
13.	Himachal Pradesh	304.3	30.	Tamil Nadu	12,504
14.	Jammu and Kashmir	1792	31.	Tripura	360
15.	Jharkhand	1710	32.	Uttar Pradesh	11.585
16.	Karnataka	6500	33.	Uttaranchal	752
17.	Kerala	8338	34.	West Bengal	12,557

Total waste generated = 127,485.107 MT/day

generated in India is openly dumped or burnt leading to contamination of the surrounding environment [11, 16, 18, 36, 40, 41, 58].

A systemic approach is required to improve various policies, rules, regulations and legal framework so as to achieve sustainable solid waste management in the Asian countries [51]. An effective waste management system utilizes data including quantity, quality and composition (both physical and chemical) of waste (from different socio-economic groups) for determining an effective solid waste management system. As such, these parameters depend on number of varied factors like living standards, seasonal variations, food habits, source of generation and socio-economic conditions of the area [1, 9, 13, 19, 22–25, 27–29, 42, 50]. As such, the characterization study helps in determining the existing deficiencies in the MSW management system practices and can help in identifying appropriate steps for minimizing the existing deficiencies in the MSW management process [28, 29]. Another approach successfully utilized for identifying potential drawbacks in the existing MSW management system is the use of 'waste-aware' benchmark indicators which includes qualitative and quantitative indicators for the assessment [46, 60–62]. The quantitative indicators of 'waste-aware' benchmark indicators are part of the physical component and comprises of Public Health-collection, Environmental controlled disposal and Resource Management—reuse, reduce and recycling (as percentages) whereas the qualitative indicators are part of governance covering user and provider inclusivity; financial sustainability; and the national policy framework and local institutions. It is important to note that any number of indicators or parameters might be used for evaluating quality of waste management system but the efficiency and success of the process depends on the accurate information regarding the population and per capita generation rate of the MSW, physical and chemical characterization of MSW, availability of technical infrastructure and awareness among the people regarding the issues associated with improper MSW management systems [24].

For a sustainable waste management strategy it is first necessary to identify the nature and composition of the waste [22, 49, 52, 55]. In India it has been reported that the organic fraction of MSW vary between 35 and 60% in different parts of country [42]. The organic material includes paper, plastics, yard waste, food waste, wood, textiles and disposable diapers [14, 15, 55, 56, 63, 64]. The organic matter in MSW in developing countries like India is much higher than that in the waste in developed countries [33, 54, 55]. An overview of composition of MSW in Indian cities is presented in Table 2. India has a potential of producing about 4.3 millions of compost each year [49], but poor solid waste management practices and low quality of compost production causes huge constraints in exploring such large amount of plant nutrients which in turn can be helpful in increasing crop productivity [50]. Environmentally sound facilities for the treatment and disposal of MSW are in great shortage and rag picking is one activity

Table 2 Composition of MSW in Indian cities (CPCB 2015)

City	Category of city	Paper*	Textile*	Leather*	Plastic*	Metals*	Glass*	Ash*	Organic matter*	Moisture content*
Ahmadabad	Tier-II	6.0	1.0	–	3.0	–	–	50.0	41.0	32.0
Bengaluru	Tier-I	8.0	5.0	–	6.0	3.0	6.0	27.0	52.0	35.0
Bhopal	Tier-II	10.0	5.0	2.0	2.0	–	1.0	35.0	52.0	43.0
Mumbai	Tier-I	12.0	4.6	0.4	2.0	–	0.2	44.0	62.0	54.0
Delhi	Tier-I	6.8	5.6	0.6	1.5	2.9	1.7	51.5	54.0	50.0
Hyderabad	Tier-I	7.0	1.7	–	1.3	–	–	50.0	51.0	50.0
Jaipur	Tier-II	6.0	2.0	–	1.0	–	2.0	47.0	45.0	40.0
Lucknow	Tier-II	4.0	2.0	–	4.0	1.0	–	50.0	49.0	60.0
Ludhiana	Tier-II	3.0	6.0	–	5.0	2.0	–	50.0	45.0	50.0
Pune	Tier-II	5.0	–	–	5.0	–	10.0	15.0	55.0	40.0
Surat	Tier-II	4.0	5.0	–	3.0	–	3.0	45.0	40.0	30.0
Kolkata	Tier-I	10.0	5.5	0.5	1.7	0.4	1.6	50.0	51.0	46.0
Puducherry	Tier-II	11.0	4.0	–	2.0	0.2	1.5	26.0	50.0	54.0

* Values are in %

that is feared to be causing steep decrease in the calorific value of the waste due to implicit recycling activity. Presently, lack of data as well as information regarding the generation, amount and nature of MSW creates hurdle in developing an integrated MSW management plan.

In this context, majority of the studies reported for India are primarily based on Metropolitan and Tier-I cities. Very limited studies have been reported for characterization of municipal solid wastes in Tier-II cities of India which are often state capitals or designated industrial hubs with a population of about 1 million. As such, the present paper focuses on characterization of MSW from Tricities of Chandigarh, Mohali and Panchkula, top tier-II cities in Northern India. The main objectives of the study were to analyze the physical and chemical characteristics of MSW in all the three cities, for assessing suitable waste processing technologies, to understand present waste management and identifying factors responsible for inefficient waste management in these cities and to suggest suitable remedial measures. Further, no characterization studies of these cities have been reported in literature earlier which adds to the novelty aspect of the research work carried out in the context of these cities. Furthermore, the characterization results will be submitted to the Tricity municipal corporations so that an effective management of MSW can be set up for the future.

Site location

Chandigarh has a population of 1.05 million as per census 2011 with a growth rate of 17% in a decade (2001–2010) covering an area of 114 km^2 [10, 46]. Presently, the city is divided into 56 sectors. The overall municipal Solid waste generation in Chandigarh is 380 Tons/day (TPD) [47, Personal communication with an employee of Chandigarh Municipal Corporation, 2016].

Mohali has a population of 9, 86,147 in 2011 [10, 47] with an area of 1160 km^2. It is divided into 3 tehsils comprising 3 development blocks and the entire city is divided in 115 sectors and phases. Mohali Municipal Corporation is responsible for management of solid waste in city. Municipal Solid waste generated in Mohali is 150 tons/day (150TPD).

Panchkula covers an area of 816 km^2 having a population of 5, 61,293 in 2011 as per the latest Indian census report [10, 47]. The entire city is divided in 30 sectors and the municipal solid waste generated is same as Mohali (150TPD) [47, Personal communication with employee of Panchkula Municipal Corporation, 2016]. Figure 1 shows the location of Chandigarh, Mohali and Panchkula cities along with the three dumping sites.

Materials and methods

Sample collection

The sampling procedures followed in the study were as per the guidelines described in*ASTM-D5231-92* [4–8]. Samples from all three cities were collected from vehicles unloading waste from commercial, institutional and household waste at the dumping sites. In accordance with the method, vehicles identified from the designated regions reaching the dumping sites were selected arbitrarily throughout each day of the 10 days sampling period to have an illustrative waste stream. A total of thirty samples ($n = 10$ for each site) were utilized for the study purposes. Sampling of

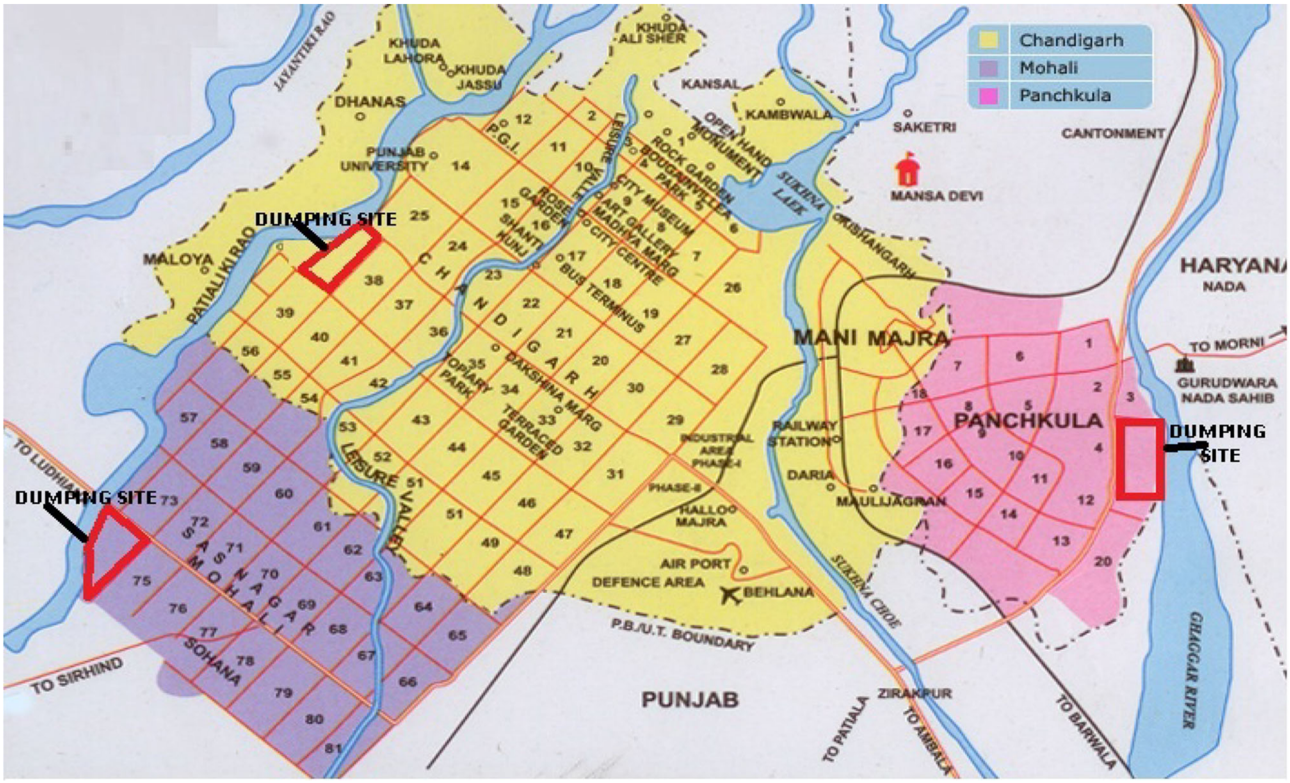

Fig. 1 Location of Tricity along with the dumping sites (*red marked areas* denote the dumping grounds in these cities)

waste from all the three cities was done for five groups including Commercial (comm.), Low Income Group (LIG), Middle Income Group (MIG), High Income Group (HIG) and Institution (Inst.). In particular, majority of the characterization studies are utilized including different socio-economic groups using High Income Group (HIG), Low Income Group (LIG), and Medium Income Group (MIG). However, in this study we have incorporated two more categories including institutional and commercial. This is because over the period of time it has been observed in the Tricity area that there has been rapid growth of MSW generated from institutional (universities, colleges, coaching centres) with about 10% in Chandigarh, 6% in Mohali and 6% in Panchkula and commercial (shopping complexes, malls and restaurants, local markets) and are now responsible for accounting for about 10% in Chandigarh and 7% each in Mohali and Panchkula of the total MSW generated in the Tricity region. The samples were collected using quartile method to understand the waste composition [57]. All the contents in the vehicles were emptied on a plastic sheet for preventing mixing of soil or any beneath water; 1000 kg of the waste sample unloaded from the vehicles was then reduced to 100 kg in second iteration. Segregation of the waste sample was done manually with the help of workers and rag pickers.

Physical characterization of municipal solid waste

Determination of the physical composition of MSW is highly important as it helps in ascertaining the suitable technology for implementation of an effective waste management system [57]. The samples collected were analyzed on wet weight basis (without any prior drying of waste samples for removal of moisture) and segregated into their components. Segregation of the waste helps in properly disposing the vast amount of waste. The segregated component includes paper, polythene/plastic, clothes/textiles, organics/vegetables/horticulture, rubber/leather, glass, other mixed constituents like clothing, toy and sanitary items metals and inert. Inert wastes are generally defined as those wastes which are non-reactive chemically and cannot be degraded biologically by microbes. In our present study, the inert materials present in the MSW characterization for all the three cities were gravel, sand and stones. The reason for inert component in the MSW for the Tricity region is primarily due to construction of buildings which are collected via street sweepings and disposed of at the MSW dumpsite.

Each component of the waste was weighed separately to know the percentage contribution to the waste. Moisture content of the waste was immediately analyzed in the laboratory as delaying can alter the characteristic properties of waste and thereafter sample preparations were done for chemical characteristics.

Chemical characterization of municipal solid waste

The proximate and ultimate analysis of the MSW was also performed to determine the fraction of crustal elements and ash content of the MSW as physical characterization provides information only regarding the main component fraction present in MSW [3, 57]. Sample preparation was done as per BIS-IS: 9234 and ASTM-D5231-92 [4–8]. Various analyzed parameters include moisture content, volatile matter, ash content, fixed carbon and elemental analysis (C, H, N, S and O). The gross calorific value was determined using bomb calorimeter (Model 6200 Spectronics) in the laboratory.

Results and discussion

Physical characterization

The physical characterization plays an important role in characterization of a waste stream, results of which indicate fraction of organics, inert and recyclables present in the MSW which help in determining the treatment procedures for MSW. The results of physical characterization of MSW from Chandigarh, Mohali and Panchkula are presented in Table 3. The Miscellaneous waste generally includes waste like thermocol, coconut, straw/hay, foam and dry leaves.

Density of MSW play an important role in deciding various processes of the waste handling starting from collection of the waste to its storage as well as transportation of the waste. In our present study, it was observed that due to higher percentage of compostable and inert fractions the bulk density of wastes from all the three cities was high. The density of the waste of Chandigarh, Mohali and Panchkula was reported to be 500.8 kg/m^3, 465 kg/m^3 and 432 kg/m^3 respectively. It was observed that the major fraction of the MSW from the various socio-economic groups of the three cities of Chandigarh, Mohali and Panchkula includes organic material ranging from 24.1 to 59% of the total MSW followed by inert with composition ranging from approximately 22–33%.

The biodegradables comprise mainly fruits and vegetables generated from diverse socio-economic groups of the three cities. The MSW collected from the LIG areas contained maximum organic fraction for all the three cities. The results are similar to other reported literature wherein it has been stated that with decrease in socio-economic status on area, organic fraction of the waste increases [20, 42]. Other studies have also showed that developing nations generate organic waste as a major fraction [28–30, 34, 35, 40, 41]. A study conducted to analyze the MSW generation in developing countries like Nepal, Pakistan, Bangladesh and Sri Lanka concluded that these countries have high percentage of organic matter (40–70%) with high moisture content, which makes them unsuitable for incineration [30].

The high content of inert fraction in the Tricity region is predominantly due to continuous unrestrained practice of combining street sweeping waste and construction and demolition with MSW. The presence of inert increases the density and decreases the calorific value of the refuse [50]. Similar characterization studies performed in Jalandhar city reported that the MSW contained approximately 21–33% of inert [50], which is almost similar to the percentage of inert contained in the MSW from the Tricities. Another case study in Pune city indicates the presence of around 26% inert matter in the MSW [37]. Few studies conducted on the metropolitan cities like Delhi, Bangalore and Ahmedabad have also specified that MSW contained approximately 27–55% of inert fractions [40].

The inorganic fraction in the Tricity region primarily consists of paper, plastic, cardboard, polythene, rubber, leather, metals and glass. The physical characterization results show that the inorganic fraction of the Municipal Solid Waste in Chandigarh, Mohali and Panchkula (Tricity) were found to be 17.4, 15.1 and 15.7% respectively. Chief contributions of the inorganic fractions for the Tricity regions were of plastics (7.3% Chandigarh, 6.6% Mohali and 7.06% Panchkula), paper (6.1% Chandigarh, 5.3% Mohali and 5.4% Panchkula). The quantities of the metals as well as rubber and leather were less in waste owing to the informal recycling and segregation of the waste by the waste handlers before it reaches the dumping ground. It was observed from the results that major fractions of inorganics were generated from commercial, institutional and HIG areas suggesting the use of more packaged and disposable products in these sectors. Further examination of the characterization results showed that, the highest value of inorganics was observed for Chandigarh city, it being more commercialized and developed in comparison to Mohali and Panchkula. The quantities of the metals as well as rubber and leather were less in waste owing to the informal recycling and segregation of the waste by the waste handlers before it reaches the dumping ground.

Chemical characterization

The physical characterization of the MSW provides information regarding the main fraction of the waste stream, however; only the physical characterization of the MSW is

Table 3 Physical characteristics of the MSW in three cities of Chandigarh (CHD), Mohali (MOH) and Panchkula (PKL)

Components	Commercial (%)			HIG (%)			MIG (%)		
	CHD	MOH	PKL	CHD	MOH	PKL	CHD	MOH	PKL
Density (Kg/m^3)	580 ± 4.1	480 ± 7.6	390 ± 5.7	490 ± 8.7	395 ± 2.9	380 ± 2.1	500 ± 2.4	430 ± 8.7	490 ± 6.1
Compostable*	56.4 ± 4.46	52.6 ± 2.88	49.4 ± 3.56	48.9 ± 3.67	46 ± 6.1	38.8 ± 3.2	59 ± 4.6	53.9 ± 2.56	49.1 ± 8.2
Paper/cardboard*	4.2 ± 1.8	2.5 ± 1.9	3.5 ± 1.9	7.0 ± 2.1	7.8 ± 1.8	7.3 ± 0.7	5.2 ± 0.77	4.5 ± 2.98	5.2 ± 3.3
Plastics/polythene*	6.6 ± 1.88	7.3 ± 3.44	6.4 ± 2.8	8.2 ± 6.7	8.0 ± 1.44	8.5 ± 2.9	6.2 ± 1.1	5.7 ± 1.7	5.9 ± 0.77
Glass*	0.4 ± 1.1	0.2 ± 1.61	0.8 ± 1.09	1.8 ± 0.6	1.9 ± 4.10	1.22 ± 1.8	1.4 ± 2.1	1.0 ± 2	1.4 ± 0.45
Rubber/leather*	0.6 ± 1.72	0.1 ± 0.16	0.2 ± 0.17	2 ± 5.23	1.9 ± 0.03	1.7 ± 1.2	0.5 ± 6.1	0.7 ± 0.04	0.53 ± 2
Metals*	0.2 ± 0.34	1.0 ± 1.78	0.6 ± 1.1	0.1 ± 0.03	0.1 ± 1.6	0.5 ± 1.7	0.1 ± 0.3	0.1 ± 0.03	0.2 ± 0.1
Inert[a]*	28.5 ± 9.2	29.4 ± 4.66	29 ± 9.66	29 ± 2.3	30.1 ± 9.6	30.8 ± 5.7	22 ± 1.7	25 ± 1.58	25.2 ± 4.3
Miscellaneous[b]*	3.5 ± 1.6	7.6 ± 1.56	10.1 ± 5.84	3 ± 2.87	4.2 ± 3.89	11.7 ± 3.3	5.6 ± 1.56	9.3 ± 5.29	12.5 ± 7.4
Total	100	100	100	100	100	100	100	100	100
Components	**LIG (%)**			**Institutional (%)**			**Average**		
	CHD	MOH	PKL	CHD	MOH	PKL	CHD	MOH	PKL
Density (Kg/m^3)	550 ± 8.7	550 ± 8.8	487 ± 7.8	384 ± 2.99	470 ± 4.6	410 ± 7.6	500.8	465	432
Compostable*	58.1 ± 2.9	54.9 ± 1.4	51.5 ± 3.4	35.6 ± 2.1	26.4 ± 2.76	24.1 ± 3.34	52	46.7	42.58
Paper/cardboard*	5.1 ± 3.8	4.6 ± 2.9	3.8 ± 1.40	8.6 ± 2.4	7.4 ± 1.7	7.3 ± 6.8	6.0	5.3	5.432
Plastics/polythene*	5.1 ± 1.16	4.7 ± 0.2	4.6 ± 1.80	10.6 ± 3.9	9.4 ± 8.9	9.9 ± 7.2	7.3	6.6	7.06
Glass*	0.1 ± 1.4	0.4 ± 3.1	0.1 ± 1.68	4.3 ± 2.75	3.9 ± 0.23	3.7 ± 1.5	1.6	1.4	1.44
Rubber/leather*	0.9 ± 1.56	0.5 ± 0.02	0.4 ± 1	4.5 ± 0.45	3.2 ± 0.23	3.1 ± 0.01	1.7	1.2	1.186
Metals*	1 ± 0.02	0.1 ± 1.7	0.1 ± 0.01	2.7 ± 0.01	2.0 ± 1.3	2.0 ± 0.4	0.8	0.6	0.68
Inert[a]*	28.7 ± 1.34	32.2 ± 7	33 ± 6.1	26.9 ± 5.62	26.3 ± 7.9	24.3 ± 6.6	27.0	28.6	28.46
Miscellaneous[b]*	1 ± 3.3	2.6 ± 1.7	7 ± 5.9	7.6 ± 6.6	21.3 ± 2.19	25.6 ± 4.57	4.1	9	13.378
Total	100	100	100	100	100	100	100	100	100

Number in parentheses is standard deviation

HIG high income group, *MIG* medium income group, *LIG* low income group

*Values in percentage (%)

[a] * Includes waste from building construction, gravel, sand and stones

[b] * Includes waste like thermocol, coconut, straw/hay, foam and dry leaves

not adequate as chemical characterization helps in deciding the future course of treatment processes by giving the percentage of crustal elements present in MSW. It is essential to carry out the ultimate and proximate analysis for selection of suitable technology for future treatment processes. The results of proximate and ultimate analysis of the MSW of Chandigarh, Mohali and Panchkula are given in Table 4.

Wet moisture content of the MSW for Chandigarh, Mohali and Panchkula were observed to be in range of 42–59%, 34–57.7% and 35–44% respectively. It has been earlier reported that the moisture content for Asian countries varies between 17 and 65% [32, 33, 41, 42] and the moisture content observed from the Tricity region was well within the limits as observed for Asian countries. Studies conducted in Delhi and Ahmedabad also show the moisture content in the MSW lies in the range 24–9% [30]. The moisture content plays an important role in understanding the nature of the waste as high moisture content indicates presence of higher fraction of organic and putrescible materials. Moisture content was highest in LIG areas of all the three cities indicating presence of higher fractions of vegetables and other putrescible constituents. The ash content of the MSW of all the three cities was observed to be high due to large amount of inert material in waste samples. The combined average ash content of low-income group from all the three cities was reported to be 23.7% (23.3% in Chandigarh, and 21.6% in Mohali and 26.2% in Panchkula). Such findings had also been observed for a study carried out in Delhi wherein ash content of 21.8% was reported from LIG area in Delhi [56].

The knowledge of calorific value of MSW is necessary for designing the energy recovery from the MSW. MSW characteristic studies conducted in metropolitan cities of Delhi and Mumbai [31, 42] indicated the approximate calorific values for these cities as 4498 kcal/kg and 7477 kcal/kg, respectively. The calorific value of the MSW of Chandigarh, Mohali and Panchkula was found to be significantly high in HIG (2508 kcal/kg in CHD, 2208 kcal/kg in MOH and 1500 kcal/kg in PKL) followed by the commercial area (2200 kcal/kg in CHD, 2186 kcal/kg in MOH and 2218 kcal/kg in PKL) and lowest in LIG (1008 kcal/kg in CHD, 1005 kcal/kg in MOH and 1123 kcal/kg in PKL). This is primarily due to the presence of higher combustible fractions of waste in HIG and commercial sector in comparison to LIG wherein more organic fraction and higher moisture content was observed.

The C/N ratio varies from 22.9 to 28, 19 to 25.9 and 24.6 to 29 for Chandigarh, Mohali and Panchkula, respectively. The reported literature mentions that C/N ratio for Asian countries varies from 17 to 52% [33, 42]. The elemental composition analysis indicated higher average concentration of C (34.18% in CHD, 33.8% in MOH and 31.9% in PKL) followed by O (11.41% in CHD, 10.2% in MOH and 11.1% in PKL), H (4.42% in CHD, 4.2% in both MOH and PKL) and N (1.35% in CHD, 1.53% in MOH and 1.1% in PKL). The importance of the elemental composition of the waste helps in determining the type and hence treatment potential of the waste components and also helps in developing the stoichiometric equations to compute gaseous byproducts for treatment of MSW [31].

In comparison with the latest reported literature from CPCB [12] of other similar cities in India, the amount of solid waste generated was almost similar as shown in Table 2. Further, other similarities of the results were observed with other reported literature including higher organic fraction in LIG and more calorific value and combustible fractions in HIG for all the three cities. Also, the results of moisture content and the C/N ratio observed from the Tricity region suggests that the MSW generated from these cities is highly amenable for composting and less suited for incineration purposes.

Existing waste processing techniques in Tricity region

Refuse derived fuel (RDF)

There exists a refuse derived fuel (RDF) plant having an overall capacity of 500 tons has been working under the name of Green Tech Fuel Processing Plant in Chandigarh city. The company is responsible for complete processing of the MSW and the RDF generated has calorific value of 3100 kcal/kg with moisture content less than 15%. One of the significant challenges faced by the RDF plant is the lack of potential buyers for the RDF produced, thereby incurring heavy financial losses. Except this, no other Public Private Partnerships (PPP) alternatives exist for Chandigarh and no such PPP initiatives exist in Mohali and Panchkula Municipal Corporation. Wastes collected from Mohali and Panchkula and other nearby states (e.g., Shimla from Himachal Pradesh) send their MSW to the RDF operating plant in Chandigarh for treatment. Waste fractions not utilized by the RDF unit are returned and openly dumped. In hindsight, lack of such PPP collaborations is leading to high negligence in management of solid waste in both Mohali and Panchkula city.

Burning/incineration

The Municipal Corporations of Tricities do not follow incineration of the MSW generated due to the presence of high moisture content and inert. However, waste generated

Table 4 Chemical characteristics of the MSW in three cities of Chandigarh (CHD), Mohali (MOH) and Panchkula (PKL)

Components	Commercial (%)			HIG (%)			MIG (%)		
	CHD	MOH	PKL	CHD	MOH	PKL	CHD	MOH	PKL
Proximate analysis									
Moisture content*	59 ± 7.8	49 ± 5.66	44 ± 5.2	49 ± 3.9	44.6 ± 2.1	37 ± 1.76	42 ± 2.44	43.6 ± 7.1	38 ± 1.77
Volatile matter*	17.7 ± 4.5	21 ± 4.54	21.6 ± 5	25.8 ± 3.2	28.65 ± 2.3	28.21 ± 2.2	28 ± 7.65	25.1 ± 6.4	25.9 ± 4.06
Ash content*	22.4 ± 5.7	28.8 ± 4.1	30.2 ± 4.8	24.7 ± 6.56	24.95 ± 4	29 ± 6.1	26.4 ± 6.70	28.5 ± 7	28.8 ± 4.98
Fixed carbon*	1.0 ± 4	1.99 ± 0.1	4.2 ± 3.8	0.8 ± 6	1.82 ± 7.12	5.79 ± 1.66	3.67 ± 0.76	2.8 ± 5.23	7.3 ± 0.6
Gross calorific value (GCV)[a*]	2200 ± 41.8	2186 ± 128.6	2218 ± 324	2508 ± 145	2208 ± 206	1500 ± 291.5	1729 ± 160.2	1421 ± 96.1	1540 ± 116
Ultimate analysis									
Carbon*	33.6 ± 2.03	30 ± 30.2	29.8 ± 2.30	37 ± 3.61	36.01 ± 4.18	35.3 ± 4.32	34.4 ± 6	32.9 ± 5.45	32.19 ± 2.32
Hydrogen*	3.90 ± 1.45	4.56 ± 1.34	4.2 ± 2.2	4.6 ± 2.98	4.08 ± ±1.76	3.40 ± 1.66	6.6 ± 2.67	4.9 ± 6.52	5 ± 2
Sulfur*	1.0 ± 0.001	0.001 ± 0.1	ND	ND	ND	ND	ND	ND	ND
Nitrogen*	1.2 ± 1.76	1.4 ± 1.45	1.06 ± 0.001	1.4 ± 1.66	1.39 ± 0.12	1.2 ± 0.08	1.5 ± 6.3	1.48 ± 2.30	1.2 ± 1.11
Oxygen*	12.6 ± 6.43	12.9 ± 6.22	14.2 ± 7.87	12.5 ± 8	10 ± 2.61	10.01 ± 1.58	6.9 ± 3.4	5.8 ± 5.45	6.2 ± 2.33
Mineral content	47.7	51.2	51.7	44.5	48.5	50.09	50.6	54.9	55.4
C/N ratio	28	21.4	28.1	26.4	25.9	29	22.9	22.2	26

Components	LIG (%)			Institutional (%)			Average		
	CHD	MOH	PKL	CHD	MOH	PKL	CHD	MOH	PKL
Proximate analysis									
Moisture content*	58.9 ± 8.2	57.7 ± 9.26	44 ± 6.71	42.01 ± 6.66	34 ± 5.21	35 ± 7	50.18	45.78	39.6
Volatile matter*	17 ± 2	17.6 ± 6.1	25 ± 5	24.8 ± 4.10	24.9 ± 2.5	25.3 ± 4.65	22.66	23.45	25.2
Ash content*	23.3 ± 4	21.6 ± 6.1	26.2 ± 7.8	32.9 ± 3.4	33.7 ± 7.5	35.3 ± 8.5	25.94	27.51	29.9
Fixed carbon*	1.0 ± 1.89	3.1 ± 5.6	5.7 ± 5	0.5 ± 6.59	7.6 ± 4.56	4.4 ± 7.4	1.39	3.4	5.4
Gross calorific value (GCV)[a*]	1008 ± 56.8	1005 ± 88	1123 ± 138	2200 ± 459	2185 ± 233	1329 ± 132	1929	1801	1542
Ultimate analysis									
Carbon*	32.9 ± 8.9	34.55 ± 7	32 ± 8.5	33 ± 2.13	35.9 ± 0.66	30 ± 2.56	34.18	33.8	31.9
Hydrogen*	3.9 ± 1.77	4.0 ± 6.12	4.56 ± 2.34	3.10 ± 1.77	3.78 ± 1.43	4.09 ± 1.23	4.42	4.2	4.2
Sulfur*	ND	0.001 ± 0.008	0.001 ± 0.01	ND	ND	ND	0.2	0.004	0.001
Nitrogen*	1.35 ± 0.67	1.49 ± 1.34	1.3 ± 2.66	1.3 ± 2.45	1.89 ± 3.91	1.08 ± 7	1.35	1.53	1.1
Oxygen*	14.1 ± 6.43	13.3 ± 4.21	14 ± 6.41	10.99 ± 2.56	9.06 ± 0.04	11.2 ± 1.12	11.41	10.2	11.1
Mineral content	47.7	46.9	48.1	51.6	49.3	53.1	48.43	50.1	45.6
C/N ratio	24.3	23.1	24.6	25.3	19	28.2	25.3	22.1	27.1

Number in parentheses is standard deviation

HIG high income group, *MIG* medium income group, *LIG* low income group

* Values in percentage (%)

[a*] GCV Gross calorific value (Kcal/Kg)

from the health facilities is generally treated by incineration process (Personal communication with Chandigarh, Mohali and Panchkula Municipal Corporation, 2015). Few occurrences of the illegal burning of the waste in open or dumping grounds have been reported in all the three cities. As such this process is an ineffective method for SWM system and heavily pollutes the nearby areas in the vicinity due to this process.

Alternatives to existing waste processing techniques based on characterization analysis

There seems to be a dire need for the development of an integrated MSW management facility for Chandigarh, Mohali and Panchkula cities based on the characterization results. The unified waste management facility must be in compliance with the Solid Waste Management Rules, 2016 [39]. Based on the characterization results analysis carried out for the Tricity region, the following suitable alternatives are suggested.

Source segregation

The physical characterization of the three cities indicates that the MSW contains more than 55% of the organic fraction and around 34% inert fraction. As such, the process of source segregation of wastes should be immediately implemented. This can be achieved by educating the residents of the Tricity about the importance of the source segregation and its effective role in solid waste management. In particular, mixed fraction of waste reduces the overall energy content of MSW. Segregation of the combustible material at source would also help the RDF plant in Chandigarh city to generate better quality and quantity of fuel. The street sweepings and the waste from construction activities must be strictly prohibited from getting mixed with the MSW. Separate containers or color coded containers need to be kept at the collection centers as well as in households which will further help in source segregation of the waste (segregation at source). The characterization of waste also indicated that the density of the wastes was in the range of 500.8 kg/m^3, 465 kg/m^3 and 432 kg/m^3, respectively, for Chandigarh, Mohali and Panchkula cities. In this context, for an effective management system the capacity of the bins and containers must be evaluated on the basis of population, waste generation rates as well as density of waste within the different sectors of the Tricity regions. The vehicles used for transportation of the waste from three cities must have a storage facility for the waste during rainy seasons to prevent rainwater from entering the waste.

Recycling and recovery

Recycling and recovery of waste is strongly promoted for conservation of resources and prevention of environmental degradation. The percentage of plastic recovery is approximately 40% in India which is much higher than many of the developed nations having only 10–15% of the recycling rate [17, 50, 53–55]. Unfortunately, there exists no formal recovery or recycling facilities in Tricity area. Hence, it proposed that there should be an introduction of formal recycling unit where there should be proper and formal recycling of waste so as to derive all the benefits associated with recycling process [14]. Presently, in Chandigarh and Panchkula, there exists some local non-formal recyclers involved in recycling process and these informal recyclers mainly comprises of unorganized and unrecognized establishments who do not contribute to the economy. Interestingly, even the informal recycling activities are not carried out in Mohali.

Biomethanation plant

The appropriate waste processing techniques for Chandigarh, Mohali and Panchkula cities must be implied depending upon the quantity and quality of the waste generated, economy and engendered environmental impacts. Based on the MSW characterization of the three cities, the study revealed that installation of bio-methanation plant (serving the entire Tricity region) for the organic waste should be recognized.

Composting

A single technology cannot lead to the complete management of the waste. The household or community side composting should be encouraged, as it would reduce the dumping ground burden. Numerous studies [2, 9, 19, 22, 38, 45] have recommended that composting or even vermi-composting can play a vital role in organic waste management. The physical characterization of the MSW from the three cities in Chandigarh, Mohali and Panchkula showed that more than 55% of the waste stream was organic and are dumped directly in an unscientific manner in open dumping grounds. In this context, composting is a suitable method for application in the three cities. Composting is the finest method of disposal of urban solid waste, using it on the land as organic fertilizer since it transforms the organic matter into more stable form and also lessens the waste mass and volume elated to the landfills [17, 45]. The microbial based aerobic process is usually considered as environmentally thorough technique for conversion of organic waste into organic fertilizer or soil conditioner [1, 17, 45]. Standards for composting as mentioned under the Solid Wastes Management Rules [39] contemplate waste segregation as an essential criterion for effective composting but this is not implied in many municipalities [21, 22, 49]. However, in Chandigarh city few informal sectors and certain NGO's are practicing composting process at schools and colleges.

Engineered landfill and other recommendations

It is suggested that proper-engineered sanitary landfill site must be constructed in all the three cities, i.e., Chandigarh, Mohali and Panchkula with proper leachate collection and extraction systems which would further help in controlling ground water contamination. Last but not the least; public participation is the key for successful implementation of the integrated solid waste management strategy. Citizens must be continuously briefed and encouraged for the waste minimization techniques, segregation of the waste and recycling or reuse of the waste. Proper trainings must be given to the workers who are involved in activities related to the waste management in all the three cities which should comprise information regarding occupational health hazards. Regular medical checkups of the waste handlers should be done. Active involvement of media, NGO's, schools and other educational institutes also play a vital role in communicating and guiding the public on waste management issues.

Conclusions

Management of solid waste is not a stand-alone system. Prediction of MSW generation plays a vital role in MSW management. Characterization of the waste from the Tricity region denotes that the physical characterization of the MSW from Chandigarh, Mohali and Panchkula indicate high percentage of organic matter (50%) and inert fraction (29%) in the waste stream of various socio-economic groups. The MSW collected from the LIG contained maximum organic matter. Presence of inert along with the MSW must be controlled as it spoils the processing of biodegradables as well as recyclable materials. Chemical characterization of the waste from the three cities also specified higher ash content (27.7%) due to presence of high value of inert. Public–private collaboration in the functioning of a refuse derived fuel (RDF) plant gives a light edge to these cities over other similar Tier-II cities. Based on the MSW characterization from Chandigarh, Mohali and Panchkula, it is suggested that a single existent technology like RDF cannot lead to complete management of waste, but there is a need to adopt integrated technologies for the treatment of different fractions of waste, and hence for these cities a combination of composting, vermicomposting and bio-methanation plant, would help in achieving a better solid waste management system.

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