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Seasonal characterization of municipal solid waste for selecting feasible waste treatment technology for Guwahati city, India

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ABSTRACT
As quantities and composition of municipal solid waste (MSW) vary significantly with seasons, a seasonal characterization study is critical for developing an efficient MSW management system. MSW was characterized in three different seasons for selecting an appropriate waste treatment and management strategy for Guwahati city. Results of the study shows that the major components of the MSW were organics (42.2%) and plastic wastes (25.2%), which show high variations on a seasonal basis (22–49%). The chemical characterization of MSW revealed that on seasonal basis moisture content varies between 43.4% and 58.3%, pH between 5.5 and 6.5, volatile solid content from 32.9 to 58.9%, and the calorific value between 1203 and 3015 kcal/kg. Waste collected in the present study was a mixture of organics, recyclables, and inert material which is difficult and uneconomical for treatment in its present form. However, with proper waste segregation, bio-methanation, and composting could be sustainable waste treatment solutions due to the high moisture and volatile content of the MSW. Due to inadequate quantity, low calorific values, requirement of skilled supervision, and high capital investment, the thermochemical conversion of MSW may not be economically feasible for the present case.

Implications: Present study is a novel attempt to analyze in-depth variation in the municipal solid waste (MSW) composition and properties in different seasons and how does it influence the selection and feasibility of the available waste treatment technologies. Search on Google scholar shows that only seven articles have been published till now which evaluated seasonal impact of MSW. Out to these published studies only one study have calculated energy potential of MSW on seasonal basis which is mainly restricted to incineration only. In-depth analysis of seasonal variation on anaerobic digestion, composting, refuse derived fuel (RDF), pyrolysis, and gasification is yet to determine. Furthermore, to best of our knowledge so far in India there was no such in-depth study has been published related to seasonal variation in MSW on large scale (city level). Present study provides in-depth valuable information regarding degree of variation in MSW composition and how does it affect resource recovery out of waste, which was not studied before in-depth before. Outcomes of the present study will definitely assist engineers and policymaker involved MSW management and planning for large urban areas to fulfil their sustainability goals.

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Introduction

As the world population increases, more natural resources are being consumed for industrial production to meet the rising market demands (Ikhlayel 2018). But a high pace of economic growth and urbanization also generate mammoth heaps of Municipal Solid Waste (MSW). As per a recent World Bank report, global waste generation in year 2016 was about 2.01 billion tonnes, which is expected to be 3.4 billion tonnes by 2050 (Kaza et al. 2018). The management of MSW has been a serious environmental issue in many urban areas of developing nations. Improper dumping and burning of garbage without pollution control measures is common in many developing nations such as India. Hence, a better solution is required for resolving their waste-related problems.

India is a rapidly growing country with a 31.8% growth in urbanization in the past decade. The total MSW generated in 2016 in India was about 52 million tons, which amounts to 0.14 million tons per day (TPD). This number is rapidly increasing with the country's increasing population (Narain and Sambyal 2016). Out of this massive waste, only 68% of this waste is collected, and only 19.4% of the collected MSW is treated (Kumar et al. 2017). Due to this lack of waste collection and

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treatment, generated waste is either left on an open dumping ground or burned in most of these cities (Singhal and Goel 2021a). This poor waste management leads to various health and environmental issues in urban areas (Annepu 2012; Biswas et al. 2010). So, to reduce the amount of waste going to the landfills and its associated impacts, proper MSW management and treatment system is critical for India and other developing nations.

Integrated Solid Waste Management (ISWM) approach should be used for a sustainable waste management, which can be defined as a comprehensive waste reduction, collection, recycling, treatment, and disposal system as proposed by the United States Environmental Protection Agency (USEPA). However, waste characterization must be the first step for any successful waste management program to estimate potential materials recovery, identify sources of waste generation, facilitate the designing of waste processing equipment, estimate physical & chemical properties of the waste to select appropriate treatment and maintain compliance with the environmental regulations (Ayeleru, Okonta, and Ntuli 2018). Lately, several MSW characterization studies have been conducted to identify efficient waste treatment technologies (Ayeleru, Okonta, and Ntuli 2018; Boldrin and Christensen 2010; Gómez et al. 2009; Kumar and Goel 2009; Kumar et al. 2017; Miezah et al. 2015). However, MSW composition and quantity varies considerably with seasons which directly affects the collection (primary and secondary storage of waste) and treatment scenario. Parameters like pH, moisture content, calorific value, C/N ratio of the waste can also vary with the season (Abylkhani et al. 2019; Gómez et al. 2009), which affects the overall treatment efficiency of the conventional solid waste treatment methods like composting, bio methanation, and incineration. So, to design a sustainable solid waste management system accounting for the seasonal variation in MSW is essential. Even though several studies have published on waste characterization, only few studies were published specifically on seasonal variation in MSW. Studies by (Abylkhani et al. 2019; Denafas et al. 2014; Gómez et al. 2009; Ibikunle et al. 2020; Yenice et al. 2011), were specially focused on seasonal variation in MSW and they all found minimal to considerable variation in the MSW's physico-chemical properties and composition. Aguilar-Virgen et al. (2013) found upto 8% variation in MSW composition in winter and summers among different economical groups. Furthermore, Ibikunle et al., 2020 determined the energy recovery potential of MSW incineration including the seasonal variation in MSW properties. However, effect on seasonal variation on energy and product recovery treatment options, such as biomethanation, composting, refuse-derived fuel (RDF), pyrolysis, gasification, recycling etc., is yet to determine. A holistic approach for evaluation feasible treatment options considering seasonal variation in MSW is still missing from the literature.

The present study aims to characterize MSW on a seasonal basis and assess the variation in its properties (physical and chemical) and composition. Based on these results, feasibility of different waste treatment technologies was evaluated and discussed in-depth. The largest city in North-East India, Guwahati, was selected as the study area for waste characterization. It is being developed as part of the Smart City program Government of India (GoI). The outcome of the study will assist the local and national authorities for developing MSW management plan of urban areas. Furthermore, findings and approach used in the present study for selecting feasible waste treatment option will be applicable for other regions as well as the Guwahati city is a good example of a typical urban area in the southern Asia.

Materials and methods

Study area and current waste management system

Guwahati is the biggest city in North-eastern India as well as capital city of the state of Assam, with a population of 957,352 (Census 2011). Guwahati city is situated on the southern banks of the Brahmaputra River (on 26° 10′20″ North and 91 ° 44′ 45″ East geographical coordinates). The city receives an annual rainfall of 152 to 324 cm, with heavy rains from July to mid-October. Mid-October to March is the winter season where temperature can go also low as 11°C. While summer season is from April to June typically where temperature can go as high as 38°C. The humidity prevails throughout the year but usually highest during July and August, ranging from 76 to 94%. During the late winter month, February, and the pre-monsoon period, March–April, the humidity is low, ranging between 71% and 78% in the morning and 50–57% in the evening.

Solid waste management in the city is the responsibility of Guwahati Municipal Corporation (GMC). The entire GMC area is divided into 6 divisions and 31 municipal wards (Figure 1). The city is generating about 800 MT of MSW daily. The current waste management system of the city is shown in Figure 2. Collection of MSW is done by GMC as a primary and secondary collection of the MSW. The primary collection consists of door-to-door collection of the MSW with source segregation of the waste into wet (biodegradable and inert waste) and dry waste (recyclables). After primary collection, waste is moved to the nearest community bin or

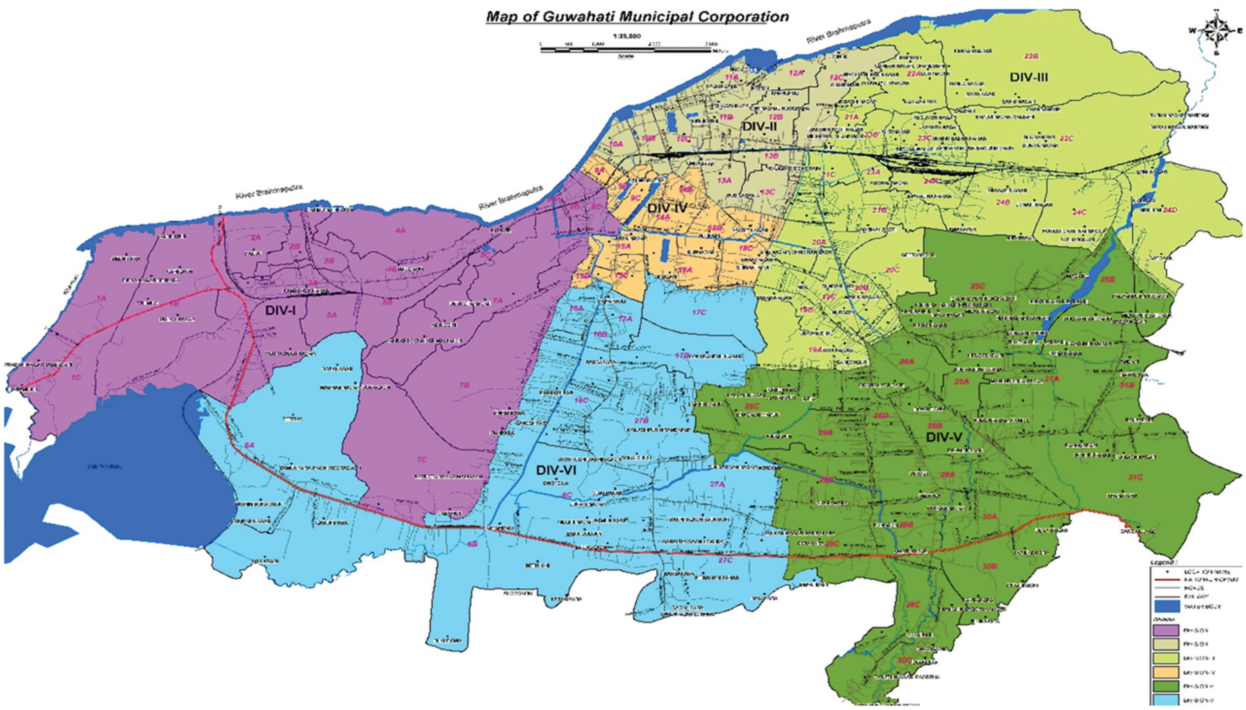

Figure 1. Divisional Map of Guwahati City (GMC portal, 2017).

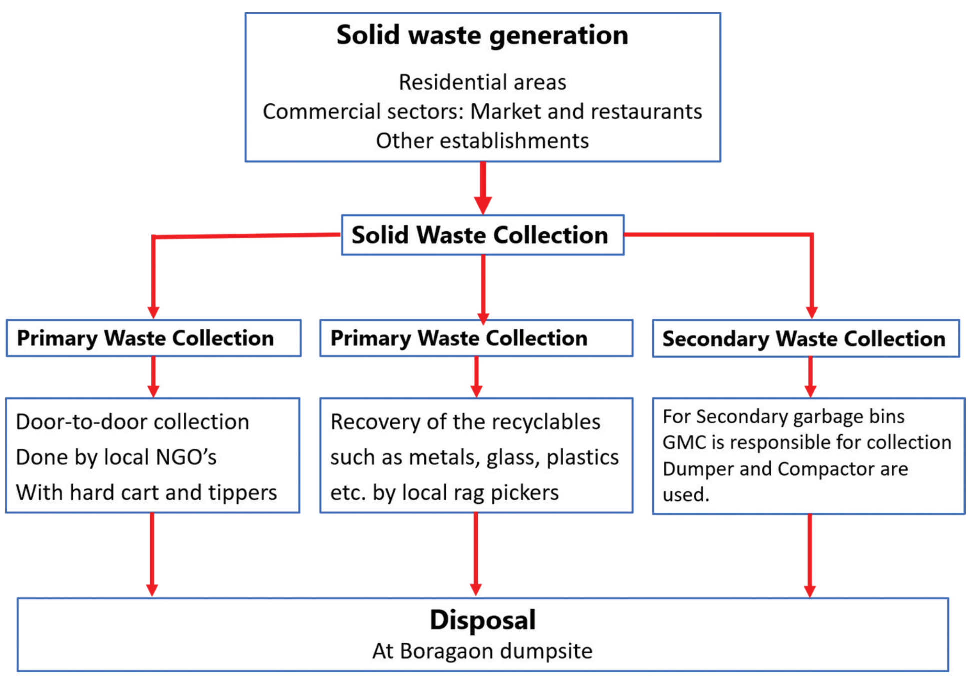

Figure 2. The current solid waste management system of Guwahati City.

transfer station with tricycles and mini-tipper trucks. In the secondary waste collection, MSW is collected from the community bins, storage depots, and transfer station using garbage compactor trucks. Due to good local awareness regarding SWM, fairly good amount of source segregated waste is collected from the households. Several local non-government organizations (NGOs) are mainly responsible for primary collection, which is also providing jobs to the local people. However, during secondary waste collection, all waste is mixed and put into a single community bin as there are no separate bins for the segregated waste. Currently, there is no waste treatment and sorting facility in the city due to which all the waste is dumped at Boragaon dumpsite which is basically an open dumpsite. According to SWM rules 2016, it is mandatory to source-segregate the waste into wet and dry waste that need to be treated safely afterward, which is a responsibility of the local municipalities. However, due to lack of financial resources and scientific knowledge, many of the India cities are still not able to manage their waste properly like Guwahati city. As the current waste management practices are unsustainable and the city was planned to be developed as a smart city by GoI, Guwahati was selected as the study area for the present study.

MSW sample collection and preparation

To characterize the MSW generated in the city, the characterization of waste was done individually for each of the city's six divisions. Also, a representative sample was prepared by mixing the waste from all the six divisions. The sampling was carried out in accordance with ASTM-D5231 – 92 – 2016 – Standard Test Method for Determination of the Composition of Unprocessed Municipal Solid Waste. The sampling was done in the three different seasons- summer (March), monsoon (August), and winter (November). A total of 32 samples were collected to provide a statistical accuracy of 90% confidence (ASTM D5231 – 92, 2016). A manual sampling protocol was followed for sampling the MSW, and samples were collected from the respective dumper/compactors from their allotted divisions. A division was chosen priory and all dumpers/compactors coming from the selected division were instructed to dump the waste separately. From that dumped waste, 32 waste samples were taken from the all the dumped loads, at different depths. Around 100 kg of the waste is collected from the MSW resulting from each division. Quartering of sampling was done to obtain a representative divisional waste sample. This sampling protocol was repeated for every division in each of the three different seasons. After collecting the samples, one representative sample was prepared using the Coning and Quartering Method number of collected samples (detailed procedure and calculates are in supplementary material). Each representative sample prepared for the divisions and the city weighing in-between 10–12 kg, which was further used for physical and chemical characterization of MSW.

Physical composition of collected samples

The MSW composition was determined as per ASTM D5231 – 92 (2016) in terms of the dry weight percentage. For determining MSW composition, samples were classified mainly into seven broad groups: organic, plastic, paper & cardboard, textile, glass, metal, and mixed residue. The physical composition of MSW was determined for all six divisions and representative sample for the three different seasons.

Chemical composition of collected samples

For chemical characterization, collected raw samples after coning and quartering procedure were taken to the Indian Institute of Technology at Guwahati. The samples were dried in an oven at 105°C for 24 hours. After drying, samples were manually shredded, ground, and sieved to prepare samples for various chemical analyses. The chemical composition of MSW was determined through the proximate analysis and ultimate analysis. Test and methods used for chemical characterization of waste are mentioned in Table 1. After determining the physical composition of the MSW, results of the study area were compared with the MSW composition of other national and international cities. Based on the physical and chemical characterization parameters, the feasibility of treatment technologies, such as biological treatment of organic waste (biomethanation, composting), recycling, and thermal waste treatment technologies (RDF, mass incineration, gasification, pyrolysis) are discussed in detail.

Results and discussion

Physical composition of MSW

The results of the seasonal determination of the physical composition of MSW carried out at Guwahati city is shown in Table 2 and represented graphically in Figure 3, S2, S3, and S4. As per the results, in all the seasons and every division of the city, organic waste

Table 1. Details of tests conducted and methods followed for chemical characterization of waste.

Sl. No.	Test name	Method	Code of practice/instrument
1	pH	SW846 9045 D	SW846
2	Moisture content	Oven dry method (E871-82)	ASTM
3	Volatile solid	IS: 10158– 1982	ISI 1982
4	CHNS-O analysis	Combustion and Pyrolysis	EuroEA3000, CHNS-O analyzer
5	Calorific value	Laboratory bomb calorimeter	Bomb Calorimeter

Table 2. Seasonal physical composition of MSW for different divisions of the city.

Division		1	2	3	4	5	6	Representative	Avg.
Organics	Aug	44.00	40.00	41.00	34.00	47.00	40.00	38.00	40.57
	Nov	46.56	50.57	48.68	53.03	44.58	44.21	39.93	46.79
	Mar	40.64	48.78	39.26	49.67	50.45	38.58	48.58	45.14
	Avg.	43.73	46.45	42.98	45.57	47.34	40.93	42.17	44.17
Plastics	Aug	29.00	28.00	31.00	23.00	30.00	35.00	27.00	29.00
	Nov	28.16	23.50	25.20	22.20	24.96	25.10	26.73	25.12
	Mar	24.14	15.83	17.04	19.97	14.63	17.24	21.77	18.66
	Avg.	27.10	22.43	24.41	21.72	23.20	25.78	25.17	24.26
Paper and Cardboard	Aug	13.00	20.00	12.00	18.00	8.00	10.00	15.00	13.71
	Nov	11.35	10.33	16.22	10.33	12.64	18.87	18.40	14.03
	Mar	10.38	10.96	22.59	11.63	9.25	19.48	15.41	14.24
	Avg.	11.58	13.76	16.94	13.32	9.96	16.12	16.27	13.99
Textiles	Aug	3.00	2.00	3.00	20.00	4.00	9.00	9.00	7.14
	Nov	3.56	1.00	1.64	8.65	1.00	1.00	1.96	2.69
	Mar	3.42	NA	2.60	3.25	3.88	2.43	4.02	2.80
	Avg.	3.33	1	2.41	10.63	2.96	4.14	4.99	4.21
Glass	Aug	1.00	1.00	2.00	0.00	4.00	0.00	0.00	1.14
	Nov	-	-	-	-	-	-	-	-
	Mar	-	-	4.44	-	2.09	2.42	-	1.28
	Avg.	0.33	0.33	2.15	0.00	2.03	0.81	0.00	0.81
Metal	Aug	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Nov	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Mar	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Avg.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mixed residue	Aug	10.00	9.00	11.00	5.00	7.00	6.00	11.00	8.43
	Nov	10.37	14.60	8.26	5.79	16.82	10.82	12.98	11.36
	Mar	20.75	24.43	14.07	15.48	19.70	19.85	10.22	17.79
	Avg.	13.71	16.01	11.11	8.76	14.51	12.22	11.40	12.53

accounts for the maximum weight percent in the overall MSW (ranging from 34 to 53 wt%). Organic waste was followed by plastics, paper, and cardboard waste in the MSW (Table 3 and Figure 3). Textile and glass accounted for 4.2 wt% and 0.8 wt%, respectively. Metals accounted for less than 0.01 wt%, because of door-to-door collection or manual scavenging of large quantities of metal waste pieces from the secondary bins by rag pickers. Due to the high percentage of recyclables and organics in MSW of the study area, recovery of recyclables and organic waste treatment methods seems to be an economical and environmentally friendly option. Table 2 shows an abrupt change in the contribution of textile waste from Division-4 in August. This may be due to local interference as division-4 is a busy market area. There is a heavy market area in division 3 and 4 while both division 3 and 1 have the major temples in the city which attracts lakhs of people from all over India. Furthermore, division 3 have all the major railway stations of the city. This could be the major reason behind the highest content of paper & cardboard and glass waste generated in division 3 compared to other divisions. While division 1 and 4 shows the highest content of plastics and textile waste respectively.

On looking at the seasonal variation in the MSW composition of the Guwahati city, organic, plastics, and mixed waste have shown significant variation. Among all types of waste, plastics have shown the most variation in the composition percentage on a seasonal basis, followed by mixed waste and organics. The highest variation in plastics and mixed waste was found in August (rainy season) and March (summers), i.e., 10.30% for plastics and 9.40% for mixed waste. The variation for organic content in MSW was up to 6.2% in the monsoon and winter seasons. The possible explanation behind these variations in MSW's composition is a change in city residents' lifestyle and consumption habits during different seasons. Besides organics, plastics, and mixed waste, other MSW components have not shown any significant variation (<5%).

Chemical characterization

The proximate analysis results for summer, monsoon, and winter for all six divisions are shown in Table 4. Results shows that MSW samples have high moisture (49.5%) and volatile solid (41.3%) content, making it an attractive option for composting or biomethanation. However, the C/N ratio of the mixed waste is low (13–14) to be used directly for any organic waste treatment method. But after

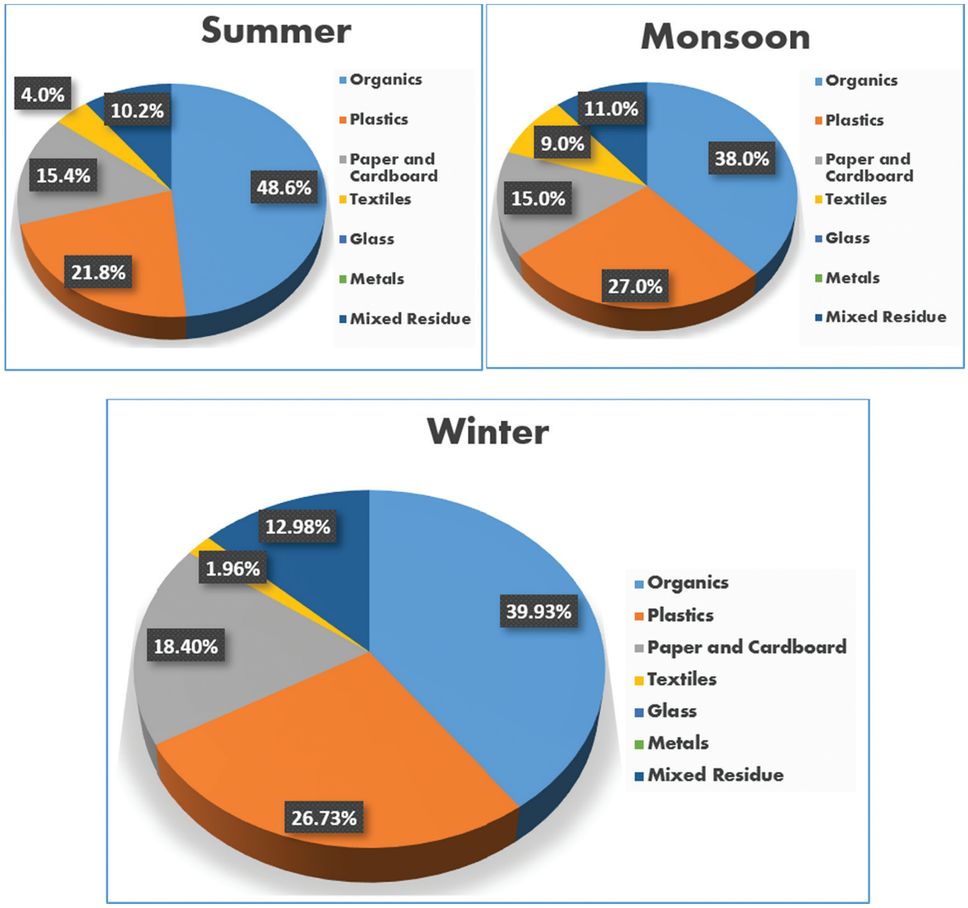

Figure 3. Seasonal composition of the MSW (representative sample) (a) Monsoon (b) Winter (c) Summer season.

Table 3. Seasonal variation of MSW composition of Guwahati city (On divisional level; *M-March, A-August, N-November*).

Sl. No.	Contents	Lowest (%)	Highest (%)	Average (%)
1	Organics	34.00 (A)	53.03 (N)	44.17
2	Plastic	14.63 (M)	35.00 (A)	24.26
3	Cardboard + paper	8.00 (A)	22.59 (M)	13.99
4	Textile	1.00 (N)	20.00 (A)	4.21
5	Glass	0.00 (A)	4.44 (M)	0.81
6	Metal	NA	NA	NA
7	Mixed residue	5.00 (A)	24.43 (M)	12.53

properly segregating the organic fraction of the municipal solid waste (OFMSW), the optimum range of C/N (25:1 to 30:1) can be achieved. The average pH of MSW is weakly acidic in nature (5.5–6.5), ranging from highly acidic to slightly acidic in different seasons. On average, MSW has a sufficient calorific value to be used for waste incineration or refuse-derived fuel.

While looking into the seasonal variation of MSW, parameters like pH, moisture content, and carbon-hydrogen-oxygen content varies significantly with the changing season (Table 5). As content of the organic waste is highest and inert waste (mixed waste) is lowest in the summer season, total volatile solid content, carbon content, and calorific value of MSW were highest in this season (Figure 3 and Table 4). This high calorific value could be the result of lower inert or ash fraction (mixed residue) and high organic fraction in the waste. Usually there is no to very little rain in the month of the November. But during the week of sample collection is little rainfall in the reason. As a result, there is high moisture content in the waste even in the winter season. There is not much variation in the average value of the pH, C/N ratio, and moisture content in the summer and rainy seasons. However, there is a significant difference in the percentage of volatile solids and calorific values during these two different seasons due to the change in MSW composition.

Comparison of MSW composition of Guwahati city with other cities

India produces the highest amount of waste compared to other South Asian countries like Pakistan, Bangladesh, Bhutan, Afghanistan, etc. (Kaza et al. 2018). Comparing the MSW from Guwahati with other

Table 4. Results of proximate and ultimate analysis of MSW samples (for different divisions and sampling times). [* = Analysis was not done; ND = Not detected].

Division		1	2	3	4	5	6	Representative	Average value
Moisture content (%)	Aug	38.1	50.3	40.7	46.7	39.7	44.6	43.8	43.4
	Nov	64.4	58.4	37.1	63.2	62.6	57.0	65.7	58.3
	Mar	37.44	46.30	52.08	46.17	43.50	54.25	48.42	46.88
pH	Aug	6.15	5.86	4.90	5.32	5.10	5.64	5.29	5.47
	Nov	6.60	6.46	5.76	6.80	5.89	7.00	6.89	6.49
	Mar	5.28	5.63	5.37	5.65	5.73	5.54	5.42	5.52
Volatile solids (%)	Aug	32.50	29.50	36.45	27.36	38.90	31.65	34.25	32.94
	Nov	37.90	28.20	37.80	37.70	25.70	31.20	26.00	32.07
	Mar	79.50	62.60	61.50	52.30	47.70	57.00	52.10	58.91
Calorific value (kcal/kg)	Aug	1454	1053	1153	1153	1253	1153	*	1203
	Nov	1354	1253	1454	903	1655	1254	1103	1282
	Mar	3309	3209	3159	2958	2908	3109	2455	3015
C (%)	Aug	18.34	6.98	18.64	11.17	40.64	28.76	*	20.75
	Nov	13.52	7.37	17.75	9.42	10.92	5.77	5.29	10.02
	Mar	50.18	35.32	35.02	34.52	25.42	38.49	28.8	35.39
H (%)	Aug	4.050	3.24	13.32	6.35	5.38	1.92	*	5.71
	Nov	22.38	11.88	30.37	16.66	19.21	9.75	8.74	17.0
	Mar	1.68	2.86	-	4.99	3.53	2.71	3.81	2.80
N (%)	Aug	1.26	0.74	3.38	1.17	2.89	1.19	*	1.66
	Nov	0.90	0.49	0.97	0.72	0.74	0.46	0.56	0.69
	Mar	3.17	2.74	2.76	2.43	2.56	2.47	2.91	2.72
S (%)	Aug	ND	ND	ND	ND	ND	ND	*	ND
	Nov	ND	ND	ND	ND	ND	ND	ND	ND
	Mar	ND	ND	ND	ND	ND	ND	ND	ND
O (%)	Aug	4.99	5.01	3.57	2.50	4.38	2.29	3.42	3.74
	Nov	4.20	9.91	8.12	11.37	11.07	8.30	10.79	9.11
	Mar	*	*	*	*	*	*	*	*
C: N	Aug	14.56	9.48	5.52	9.54	14.09	24.13	*	12.89
	Nov	15.01	15.17	18.28	13.28	14.76	12.45	9.48	14.06
	Mar	15.82	12.88	12.71	14.18	9.94	15.59	9.88	13

Table 5. Variation in chemical characteristics of MSW in Guwahati (On divisional level; *M-March, A-August, N-November*).

Sl. No.	Contents	Lowest (%)	Highest (%)	Average (%)
1	Moisture content (%)	37.10 (N)	65.70 (N)	49.54
2	pH	4.90 (A)	7.00 (N)	5.83
3	Volatile solids (%)	25.70 (N)	79.50 (M)	41.31
4	Calorific value (kcal/kg)	903 (N)	3309 (M)	1833
5	C (%)	5.29 (N)	50.18 (M)	22.05
6	H (%)	ND (M)	30.37 (N)	8.50
7	N (%)	0.464 (N)	3.38 (M)	1.69
8	S (%)	ND	ND	ND
9	O (%)	2.29 (A)	11.37 (N)	6.42
10	C:N ratio	5.52 (A)	24.13 (A)	13.32

cities in India and other countries is presented in Table S1 and S2 in the supplementary material. On comparing the physical composition of MSW of Guwahati with average values of South Asia (Table S1), the percentage of plastics, paper, cardboard, and textile waste was significantly higher, showing differences in living habits, product consumption, and economic conditions. Even though India belongs to lower-middle-income countries, the present study area's waste composition resembles more to the upper-middle-income countries' cities like Bangkok, Johannesburg, Chihuahua, and High-income countries' cities like Turku and Austin. Among all the countries mentioned in Table S1, the plastic component of the MSW of the present study area was found highest, and paper & cardboard waste was higher than most of the countries compared. On the contrary, the organic, glass, and metal content of the waste was relatively less to the other cities in the world. Lower organic content and higher plastic and paper waste content may represent the citizens' higher living standards or huge consumption of packaging and plastic products (Goel 2008; Kandakatla, Ranjan, and Goel 2017; Kaza et al. 2018). Though for most developing nations, organic content in the MSW is dominate in the MSW which is also true for the current case study (Yang, Xu, and Chai 2018). However, compared to other Indian cities, the percentage of plastics, paper, and cardboard were found significantly higher for study area even with the large metropolitan cities of the countries like Mumbai, Kolkata, and Delhi.

On comparing the chemical composition of the MSW of the present study, calorific value, carbon content, and C:N ratio of the MSW was lowest among all the compared city (Table S2). Also, the volatile content of Guwahati's MSW is low compares to most of the cities. Due to lower C: N ratio (<25–30) and volatile content (<50–60%), MSW in the present form (mixed form) will not be feasible for biological treatment. But with proper segregation of organic waste, these values can be improved for the biological process. The higher content of paper, plastics, and textiles compared to other Indian cities shows a high potential for recycling waste. Even though the waste's calorific value is lower than all the cities in Table S2, it may be adequate for incineration (>1700 kcal/kg) or RDF generation with proper segregation.

Potential treatment options for the MSW

Appropriate waste treatment technology selection is the backbone of any efficient MSW management design. The efficiency of certain waste treatment systems depends on the certain physical and chemical properties of the waste. So, the data generated in the present waste characterization study was used for determining the efficiency of different waste treatment options. Figure 4 shows the parameters tested for determining the potential of different treatment and recycling techniques.

Potential for recycling

Although recycling of the waste material is the second most preferred option in the ISWM hierarchy, the high recyclables content in the MSW from Guwahati (43.27%) implies recycling needs to be a priority. Among the recyclables, plastics and paper waste make up more than 38% of total MSW which is highest among all the cities compared in Table S1. However, this high fraction of recyclables demands proper segregation of MSW which means as per government SWM rules 2016 i.e., OFMSW and recyclables segregated as wet and dry waste respectively. Proper segregation will increase the opportunity for scientific disposal or treatment. It will also increase the recyclables' quality, leading to more revenue for the local authorities. Unlike most Indian cities, there is a relatively good source segregation system at the primary level of Guwahati's waste collection due to highly active local NGO's. But during secondary collection, all the segregated MSW is mixed into a single container. This makes the treatment of MSW challenging and renders the efforts of primary waste collection futile. Therefore, providing separate bins for recyclables and organic waste during secondary waste collection and building a material recovery facility (MRF) will improve the collection and quality of the recyclables. Besides revenue generation by selling good quality recyclables, segregated organic waste can be used for energy and compost generation by biomethanation, composting, and incineration. Detailed plan for designing waste storage and collection is ongoing in our lab using a approach from (Singhal and Goel 2021b) and will be presented as separate manuscript.

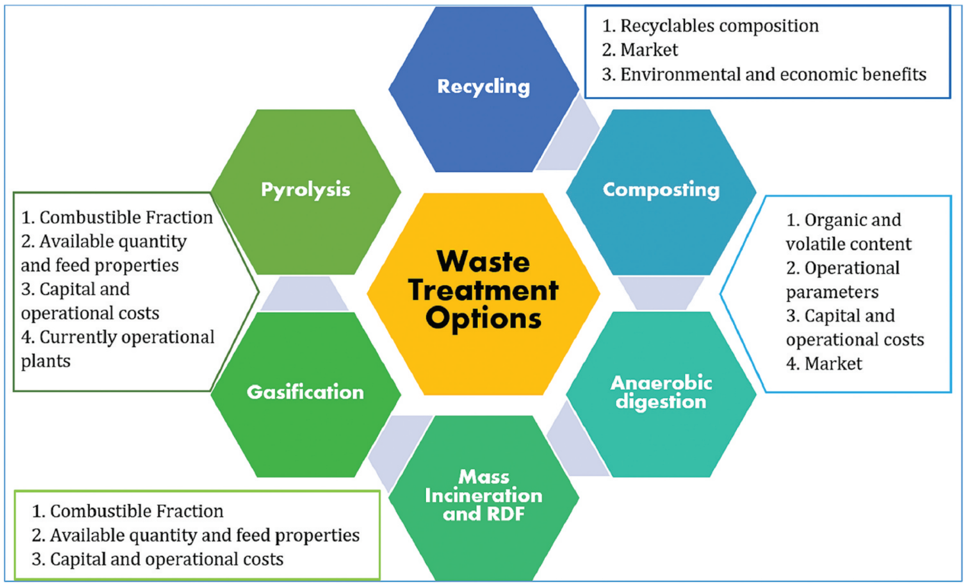

Figure 4. Parameters checked for selecting potential waste treatment technologies.

Segregation of recyclables by rag pickers was observed to be practiced at the dumpsite and in different parts of the city. So, along with centralized collection and separation of recyclables, GMC should also encourage formal & informal recyclables collection with proper training. This will help in collecting good quality recyclables and create numbers of jobs for the low-income-group of the city.

Potential for anaerobic digestion (or biomethanation)

Anaerobic digestion (AD) is a microbial degradation of biodegradable organic matter in the absence of oxygen that produces biogas and liquid slurry. Biogas is typically 50–70 wt% consists of methane, which can be used for energy generation. After stabilization, the waste slurry can be used as compost for soil amendment (Kumar and Samadder 2017; Surendra et al. 2014). AD is the next most preferred organic waste management & treatment option in the ISWM hierarchy. But operating a biogas plant requires skilled supervision and small fluctuations in pH and loading rates inside the reactor may disrupt the process completely. MSW of Guwahati city has a good moisture content (37–66%) for AD. But other parameters like volatile solid content (41.31%), C/N ratio (13.32), and pH (5.83) are not compatible with MSW to be used for biomethanation in unsegregated form. However, with waste segregation, all these parameters can be increased to the optimum level, i.e., volatile solids content more than 60–70%. C/N ratio is between 25:1 and 30:1. Also, the loading rate into the AD reactor needs to between 10% and 15% (wet system) and 20–40% (dry system) of dry content, which required the addition of water, which automatically increases the pH to the optimum range (6.50–7.50). With waste segregation and skilled supervision, biomethanation can be used efficiently for treating MSW of the Guwahati. Building a large biogas plant (>100 TPD) will require more capital investment compares to other treatment options like composting and RDF (Aleluia and Ferrão 2017; Lin et al. 2019). Also, there is huge fluctuations in the quality of the feedstock in different divisions and city has large area which result into huge waste transportation costs. So, for optimum biogas yield and to save waste transportation cost, a decentralized treatment system should be preferred over a centralized treatment system. The decentralized system may result in a high initial capital investment. Still, due to two-fold revenue generation (biogas and compost) and huge savings in waste transportation cost, in the long run, it seems like an economically sustainable solution.

This biogas can be used to generate electricity or can be converted into biofuel. According to Macias-Corral et al., (2008), around 37 mL methane can be generated from 1 g of OFMSW. Using that value, around 13,000 m^3 of methane and 21,700 m^3 of biogas (assuming methane content 60%) can be generated out of 353.5 tons of organic waste daily (total waste 800 ton/day and 44.2% of total MSW are organics) generated in the Guwahati city. As per Murphy et al. (Murphy and McKeogh 2004), 1 m^3 of biogas resulted from the AD process can generate about 2.04 kWh of electricity (conversion efficiency = 35%). So, in a single day, about

42,840 kWh of electricity can be produced from the waste, which can provide electricity to nearby 14,280 houses (average household electricity consumption is 90 kWh/month). Besides energy generation, after removing CO_2 and H_2S, methane enriched biogas containing more than 90% methane, which is somewhat like compressed natural gas (CNG). So, biogas can be used as fuel by the municipality for their waste collection fleet or used as cooking fuel for the nearby households. This will not only help in revenue generation but also help in reducing methane emission into the environment. Methane is 25 times more global warming potential (GWP) than carbon dioxide. Landfilling is one of the major sources of methane emissions in the world. So, by implementing AD treatment of MSW, huge quantities of waste can be diverted from the landfill. It will reduce methane emissions from waste, meeting India's Intended Nationally Determined Contribution (INDC) as per the Paris Climate Agreement.

Potential of composting

Composting is the biodegradation of the organic matter in the presence of oxygen results in nutrient-rich by-products that can be used for agricultural and horticulture purposes. After biomethanation, aerobic composting is the next most preferred waste management and treatment option in the ISWM hierarchy. Around 44% of the MSW generated in the study area is organic, with volatile content of 26–80% and moisture content of 37–66%. High organic and moisture content in MSW makes composting an attractive treatment option. There is a good demand for organic fertilizer in the city's nearby areas due to major government initiatives in the North-eastern region of India regarding the promotion of traditional farming. Compared to other waste treatment technologies composting requires relatively the lowest capital investment and operational and maintenance costs (Aleluia and Ferrão 2017; Annepu 2012; Lin et al. 2019). So, centralized or decentralized composting of organic waste can be an environmentally friendly and economically sustainable option for waste treatment. Another possible composting method that can be utilized is vermicomposting. Besides feedstock quality, vermicomposting's efficiency greatly depends on the vermin's health, which can be improved in a small-size treatment plant. So, Vermicomposting could be a better option than traditional window composting in a decentralized system rather than a centralized system.

But in its current form, MSW cannot be used for composting because of the unsegregated form of the waste having a low C: N ratio (ranging 5.52 to 24.13, average 13.32) and carbon content (ranging 5.3% to 50.2%, average 22.1%). With the help of proper segregation, both values can be improved to the optimum level, i.e., 25:1 to 30:1 C: N ratio and >50–60% carbon content, respectively. If needed, OFMSW can be mixed with fruit/food waste, leaves, and animal manure to reach the optimum parameters for compost feedstock (Ayeleru, Okonta, and Ntuli 2018; Tanimu et al. 2014). Besides segregation, special consideration must be given for leachate collection and treatment due to high annual rainfall in the study area. To reduce costs related to leachate collection and treatment, centralized composting seems more economical than decentralized composting in the present case. The revenue generated from the generated compost is directly in competition with other subsidizes fertilizers in the Indian market like urea. The subsidized cost of urea is around $77.5/ton, whereas the cost of city compost is around $86.7/ton. To promote organic farming and organic waste compost, the government can provide a $21.7/ton on the city compost.

Waste incineration

Where material recovery from waste is not possible, energy recovery from waste through heat, electricity, or fuel is preferred. Incineration of waste comes after the composting, biomethanation, and RDF production in the ISWM hierarchy, so these options should be preferred over incineration. Mass incineration without any pre-treatment of MSW used for electricity generation is an economical and reliable waste treatment option (Singh et al. 2011). It can reduce the mass of the waste by 70% and volume by up to 90% and recover energy from the electricity generation's waste. Compared to other waste treatment technologies, capital investment for waste incineration is highest among all the current treatment options. According to Kumar and Samadder, 2017 capital cost is required for waste-to-energy (WTE) incineration plant 400–700 $/tonne/MSW/year.

In contrast, as per Aleluia and Ferrão, (Aleluia and Ferrão 2017) the 2017 capital cost ranges from USD_{2015} 60,097 to USD_{2015} 110,581 per tons of waste processing. Also, operation expenditure per tonne is highest for incineration compares to other technologies, i.e., 5.2 to 29.9 USD_{2015}/ton; average 20 USD_{2015}/ton (Aleluia and Ferrão 2017). Since the capital investment is very high, the community's planning framework should be stable enough to allow a planning horizon of 25 years or more.

As per the World Bank report, the average calorific value of MSW for a feasible incineration operation with energy recovery should be at least 1700 kcal/kg (World Bank, 1999). According to the International Energy Agency, heating values must be greater than 1900 kcal/kg for the incineration operation to be effective and economical (Melikoglu 2013). According to the Indian SWM rules 2016, the net calorific value of waste should not be less than 1,450 kcal/kg throughout all seasons. The annual average net calorific value must not be less than 1,700 kcal/kg. The average net calorific value of MSW of Guwahati city is 1833 kcal/kg, which is appropriate for incineration as per Indian regulation and World Bank report value. However, in the rainy season average calorific value of the MSW can fall up to 1203 kcal/kg. As per waste characterization results, the waste's average moisture content was very high (average 49.5%), reaching up to high as 58.34% during the rainy season. Besides low seasonal calorific value and high moisture content, the net amount of combustible waste (42.50% of total MSW; 340 TPD) is less than 500 TPD. According to Indian regulation (SWM rules 2016), it is not economically feasible to set up an incineration plant. Due to the poor quality of feedstock and very high capital investment, installing a WTE incineration plant may not an economically feasible option for treating MSW of the Guwahati city in its present form. High moisture, variable composition, and energy content are the major difficulties the developing countries face for incinerating MSW (Annepu 2012; Kandakatla, Ranjan, and Goel 2017).

However, there are cases where MSW with low calorific values used for incineration in the WTE plant. The heating values of MSW generated in China is lower than that of India. Yet, the number of incineration plants and their capacity in China has increased more than doubled in the last decade (China Statistics Press, B. 2016). The moisture content of Japan's MSW is higher than that of India. Still, through robust source segregation, WTE contributes to more than 75% of solid waste treatment (Niyati 2015) in Japan. With proper segregation of MSW and applying some pre-treatment (thermal, mechanical, or biological), the calorific value of the waste can be increased. The moisture content of waste can be reduced via flue gas recirculation, though such options needs to be studied further (Kumar and Samadder 2017).

Refuse derived fuel (RDF)

RDF is the final product from the waste materials processed to fulfill guidelines, regulatory, or industry specifications to achieve a high calorific value as substitute fuels (Kumar and Samadder 2017). RDF is mainly used as a substitute for fossil fuels in high-energy industrial processes like power production, cement kilns, steel manufacturing, etc., to enhance these plants' economic performance (Annepu 2012). RDF could be an alternative to WTE and can be a potential waste management technology. RDF's capital investment is relatively lower than other WTE options like incineration, pyrolysis, gasification, and biomethanation (Aleluia and Ferrão 2017; Annepu 2012). Low capital investment and high combustible fraction in MSW of Guwahati city strengthen RDF's prospects as a potential waste treatment option. The average calorific value of the waste is also appropriate to be used for producing good quality RDF. The only concern is the high average moisture content of the waste, which is 49.5% and can go up to high as 65.7%. But, by proper segregation and reducing moisture content, the MSW's calorific value can be improved as RDF.

RDF could be an economically sustainable solution for waste treatment due to its huge potential to be used in nearby industries. Some cement and steel manufacturing units in the vicinity of the study area where RDF can be used as an alternative source to the coal. Also, many thermal power plants in the vicinity were closed due to corrosion of boilers due to high sulfur content in coal and difficulties in transportation of coal. These problems can be reduced by using RDF. RDF is a proven technology in India, and there are several plants operational in the country. Hyderabad (700 TPD), Vijayawada (500TPD), Jaipur (500 TPD), Chandigarh (500 TPD), Mumbai (80 TPD), Rajkot (300 TPD), Surat, Ahmedabad, Nagpur, and Kanpur are cities where RDF plants are running successfully in India (Annepu 2012). The market prices of RDF are in the range of USD 39.18 to USD 43.54 per ton. The RDF sold in the current retail market has a Gross Calorific Value (GCV) ranging from 3200 to 3800 kcal/kg. The normally used coal is usually low quality (GCV only around 50% of the RDF) and has a low cost (USD 21.77– 26.12 per ton). This low quality of coal can easily be replaced by the better quality of the RDF. This scenario makes the conversion of MSW into RDF a financially attractive treatment option.

Pyrolysis

Pyrolysis is an advanced thermal treatment method in the absence of oxygen at the temperature range of 400–800°C. In pyrolysis, at a lower temperature (500–550°C), pyrolysis oil, wax, and tar are the major products, where at high temperature (>700°C), pyrolysis gases are the main products (Kumar and Samadder 2017). Pyrolysis can result in a 50 to 90% reduction in the waste volume. It can produce fuel in different physical forms, which can be used for energy production. Also, pyrolysis has the least Global warming potential (424 GWP) compares to other WTE options like mass incineration (424 GWP) and landfilling (746 GWP), which shows it is a more environmentally friendly option compares to other WTE options (except biomethanation-222 GWP) (Zaman 2010). For quality products from the pyrolysis process, the feedstock should be of a specific type of wastes like plastic, tire, paper, wood waste, etc. Around 40–45% of the MSW generated in Guwahati has combustible materials like paper (13.9%), plastics (24.3%), textile (4.2%), leather, etc. So, pyrolysis can be used to treat paper and plastic wastes through proper segregation of waste, which alone contributed to 38.3% of the total waste in the present case. Even though pyrolysis performs well in treating specific waste streams, only a few studies reported efficient energy recovery from MSW using pyrolysis at a commercial scale. Countries like Germany, Japan, UK, and France have some plants reporting successful MSW pyrolysis plant operations for electricity generation (Panepinto et al. 2015). Capital investment ($400–700/ton of MSW/year) and operational cost ($50–80/ton of MSW/year) of pyrolysis are very high (Kumar and Samadder 2017). Especially due to the high initial investment currently, pyrolysis hasn't been much for MSW treatment. Also, it requires skilled supervision and infrastructure, which developing countries are currently lacking. So, due to high initial investment and the need for skilled supervision thrusts that pyrolysis should only be used when other treatment options are eliminated.

Gasification

Gasification is another thermal conversion technology where carbon-based material is converted into the combustible gaseous product (syngas) in an oxygen-controlled atmosphere at high temperature. Syngas is the main product from the process that can be used for energy generation or converted into liquid fuel. From an environmental impact and energy recovery prospective, pyrolysis, and gasification are more promising technologies than the incineration technology for MSW (Murphy and McKeogh 2004; Zaman 2010). Gasification and pyrolysis can reduce MSW volume up to 95% and require relatively less intensive flue gas cleaning than incineration (Yap and Nixon 2015). Even though there are not many gasification plants in India for MSW treatment, after the Indian government initiative after 2016 ("Swachh Bharat Abhiyaan"- Clean India mission), few gasification WTE plants are coming in India. All over the world, around 100 plants based on gasification technology are currently working. Japan has extensively used gasification technology (85 plants operational in 2007). Countries like the USA, Italy, UK, Germany, Norway, and Iceland have used it on a smaller scale (Panepinto et al. 2015). However, gasification technology has yet to be established at large-scale utilization across the world (predominantly in developing countries) for energy recovery from MSW due to poor efficiency of gasifiers and gas cleaning systems, high moisture content of waste, and heterogeneity in MSW composition & particle size (Kumar and Samadder 2017).

Like pyrolysis, gasification was also used mostly to treat the specific type of MSW like paper mill waste, mixed plastic waste, agricultural residue, etc. (Singh et al. 2011). Plastics and papers present in high composition (together 38.3%) in the MSW of Guwahati can effectively be used for electricity or fuel production. However, like pyrolysis, gasification also required quality feedstock, which means proper segregation of recyclables is vital for efficiently using these technologies. Besides segregation, there are other issues with using Guwahati's MSW for gasification. The moisture content of the MSW generated in Guwahati is very high (about 50%), which can also vary significantly during monsoon season and affect the waste's net calorific value. High moisture content and mixed nature of waste may lead to extensive pre-treatment of MSW (RDF), which increases the overall treatment cost of the system. The capital and operational costs for gasification are very high ($250–850/ton of MSW/year and $45–85/ton of MSW/year respectively) and may increase due to extensive pre-treatment (Kumar and Samadder 2017). Due to high capital and pre-treatment costs and high moisture content in the MSW, gasification may not be an economically sustainable waste treatment solution.

Conclusion

The study illustrated the significance of seasonal characterization of MSW to identify an effective waste management strategy. The results of the study were compared with other global and national cities of different income-level groups. Based on the experimental result data, different waste treatment technologies were reviewed for efficient waste treatment. The study results show that organics and plastics are the major constituents of the MSW (44.2% and 24.3% of total MSW). All the physical components have shown significant variation with the changing seasons. Plastics, textiles, and mixed residue have shown the most fluctuations (10.3%, 4.44%, and 9.36% difference, respectively) in the summer and monsoon. Chemical properties like pH, volatile solids, carbon, hydrogen, nitrogen, sulfur, and oxygen content have also varied significantly with seasons. The average calorific value of MSW was 1833 kcal/kg, which was remarkably high during the summer season (3015 kcal/kg) and quite low during the rainy season (1203 kcal/kg). Compared to other cities, the percentage of plastics, and paper & cardboard waste in Guwahati's MSW was very high. In contrast, organic and other waste fraction was comparable to other cites of upper-middle-income level countries.

The characterization study shows that MSW generated in Guwahati city has content of recyclables. Organic fraction of MSW and combustible rejects from the recycling facility have also high potential for producing RDF. Still, proper waste segregation is essential for economic feasibility for all the waste treatment technologies and options. In the present mixed form, the MSW of the study area is difficult and costly to treat. However, other organic waste treatment technologies like anaerobic digestion and composting could become sustainable solutions with proper segregation of the organic fraction of the waste. Due to low calorific values, low quantity of available combustible waste, huge capital investment, and high operational & management costs, thermal treatment technologies were economically unsustainable for the present case as per present conditions.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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