Characterization and Energy Generation Potential of Municipal Solid Waste from Nonengineered Landfill Sites in Himachal Pradesh, India

Anchal Sharma[1]; Rajiv Ganguly[2]; and Ashok Kumar Gupta[3]

Abstract: The paper presents the characterization and methane generation potential of municipal solid waste (MSW) generated in four nonengineered landfill sites in Himachal Pradesh located in Solan, Sundernagar, Mandi, and Baddi. The study was conducted over three seasons, including summer (April–May 2017), the rainy season (July–August 2017), and winter (November 2017) to account for seasonal variation of the waste generated. Physical characterization of the MSW generated at the study locations showed high percentages of organic waste for all three seasons. The average values of organic fractions were 55.35% (Solan), 51.87% (Sundernagar), 54.20% (Mandi), and 50.40% (Baddi). The average moisture content and density of the MSW generated varied between 42% and 51% and 465 and 552 kg/m^3, respectively, over the three seasons. The average C:N ratios over the three seasons were 32.03, 30.14, 26.57, and 23.92 for Baddi, Solan, Mandi, and Sundernagar, respectively, and hence were amenable for composting because for composting, the C:N ratio should vary between 20 and 30. The average calorific values were 2,626, 2,580, 2,476, and 2,352 kcal/kg for Baddi, Sundernagar, Mandi, and Solan, respectively, and were suitable for energy generation because the waste is suitable for waste to energy (WTE) procedures when the calorific value is greater than 2,000 kcal/kg. Further, the average methane generation varied between 11.57 and 15.78 ppm CH_4/g waste generated, making it suitable for recovery due to the presence of high organic fraction in the waste and potential waste to energy methods as discussed. The presence of methane gas indicated the potential for biogas generation from the waste and its biodegradability under the existing dumping conditions. **DOI: 10.1061/(ASCE)HZ.2153-5515.0000442.**

Author keywords: Municipal solid waste; Physical characteristics; Chemical characteristics; Heavy metals; Methane generation; Calorific value; Himachal Pradesh.

Introduction

Increased generation of municipal solid waste (MSW) and its improper management is a major environmental problem that is being experienced globally but more so for developing nations. This is primarily because of a lack of suitable treatment and disposal options in developing countries. The expeditious growth in industrialization and urbanization has led to a greater influx of population to these urban locations, thereby increasing the rate of solid waste generation (Puri et al. 2008; Sethi et al. 2013). In this context, it is important to mention that India is the second most populated country in the world (Srivastva et al. 2014; Ramachandra 2009); hence, appropriate solid waste management for urban cities in India is a significant environmental issue (Shekdar 2009; Masood et al. 2014; Sudha 2008). In particular, this is primarily because of a lack of verifiable data, including generation and characterization analysis results, leading to implementation and use of poor waste management systems (Chang and Davilla 2011; Chang et al. 2011; Hancs et al. 2011). The problem is expected to grow further, with a recent report mentioning that more than 55% of the Indian population will migrate to cities in the next 10–15 years (Gupta and Arora 2016).

The total amount of MSW generated is 127,486 t per day (TPD), out of which 89,334 TPD (70%) is collected and 15,881 TPD (13%) is processed, as reported by a Central Pollution Control Board report (CPCB 2012). Per-capita MSW generation is estimated to vary between approximately 0.2 to 0.87 kg/capita/day with per-capita generation higher in urban areas than rural areas (Rana et al. 2017). Of the total waste generated in India, 90% is dumped in open dumpsites (nonengineered landfills), leading to different sources of environmental pollution, including air, water, and soil pollution, which in turn may create serious health hazards (CPCB 2012; Rana et al. 2018; Jacob and Dharmendra 2016; Wilson 2007; Wilson et al. 2012; Sharholy et al. 2008). Disposal by composting of MSW accounts for only 5%–6% of disposal in India (Gómez et al. 2008).

Inadequate management of MSW in India exists for various reasons, including a lack of definite data on generation and characterization of wastes generated (Ogoueleka 2009; Olukanni and Mnenga 2015) and hence reduced resource allocation to collection, transportation, and disposal of waste. The problem has been further compounded by reduced budgetary provisions that worsen the existing system (Joshi and Ahmed 2016; Giusti 2009). The present management of MSW in Indian cities has almost become critical with time due to the overflowing conditions of the open landfills (Talyan et al 2008; Akhtar 2014). In the context of the situation, it is

[1]Postdoctoral Research Fellow, Dept. of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India.

[2]Associate Professor, Dept. of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India (corresponding author). ORCID: https://orcid.org/0000-0001-5356-1635. Email: rajiv.ganguly@juit.ac.in

[3]Professor and Head, Dept. of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India.

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regrettable that the efficiency of the existing waste management practices in India is extremely low. In addition to such prevailing conditions, nonsegregation of wastes and inaccurate methodology of composting techniques being carried out results in low quality of compost, which cannot be used as natural fertilizer, and other waste to energy techniques like biomethanation and refuse-derived fuel (RDF) experience poor performance (Rawat et al. 2013; Saha et al. 2010). The calorific value of the municipal solid waste ranges between 800–1,000 kcal/kg, and the C:N ratio lies in the range of 20–30.

Waste-aware analysis carried out for different categories of cities in developing countries has shown that the performance of existing MSW management practices is poor in comparison to cities of developed countries (Rana et al. 2018; Wilson 2007; Wilson et al. 2012). Characterization studies of such MSW generated in these types of cities have been reported, such as in the tricity regions of Chandigarh, Mohali, and Panchkula (Rana et al. 2018) and Jalandhar (Sethi et al. 2013). The present study locations in Himachal Pradesh follow a distinctive pattern of waste generation because the population is widely distributed, leading to growth spurts of small dumpsites, and these locations also experience wide seasonal temperature ranges affecting the functioning of the implementation of existing MSW practices. Waste-aware benchmark analysis of the study sites using the matrix method was determined to be 32% for Solan and Baddi sites and 36% for Sundernagar and Mandi sites, indicating poor implementation of existing MSW management practices (Sharma et al. 2018a). Further, the study locations are representative of tourist hotspots or are en route to other tourist destinations, thereby often misrepresenting the total waste and character of waste generated. Therefore, the waste generated in these study locations is classified as mixed wastes, with no judgment on the different socioeconomic groups or other distinguishing classifications. Proper characterization of wastes is a major factor in designing an efficient, cost-effective, and environmentally compatible waste management system (Rawat et al. 2013; Lohri et al. 2014). Characterization of solid waste can help policy makers and city planners decrease landfill waste, start adequate recycling programs, and conserve economy and resources. It can also reduce contribution of methane as a harmful greenhouse gas by using it as a green source of energy.

The present study focused on the characterization, energy, and methane potential of municipal solid waste generated at these study locations over three different seasons (summer, rainy, and winter) to eliminate any biases due to variations in population or temperature, and it also suggests some suitable improvements to techniques of waste management based on the characterization results.

Site Location

Sundernagar lies in the universal transverse mercator (UTM) zone of 43R with eastern and northern coordinates of (679652.36, 3490248.24). The MSW generation rate is 18–20 t per day, with a per-capita generation rate of 0.44 kg per day (Sharma et al. 2018a) and collection efficiency of 60%. The solid waste is disposed of in an open landfill that contributes to environment pollution.

Mandi lies in the UTM zone of 43R with eastern and northern coordinates of (682002.86, 3496499.36). The MSW generation rate is 21 t per day, with a per-capita generation of 0.44 kg per day and collection efficiency of 60% with the waste being disposed of in open landfills (Sharma et al. 2018a).

Solan lies within the UTM coordinates of (700384.18, 3420901.86) in the UTM zone of 43R. The total waste generation rate is estimated to be in the range of 21–22 t per day, with a per-capita generation rate of 0.42 kg per day (Sharma et al. 2018a). The collection efficiency of the town has been reported to be 60%, and waste is disposed of in an open landfill.

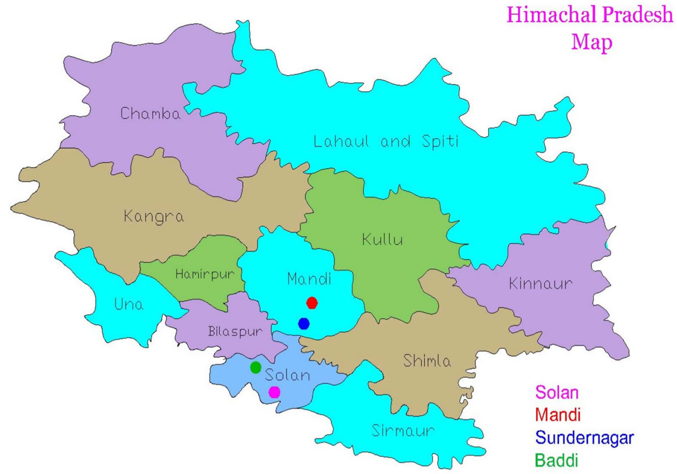

Fig. 1. Location of study regions in Himachal Pradesh, India.

Baddi lies within the UTM coordinates of (671106.39, 3426301.39) in the UT zone of 43R. The total waste generation of the town is 18 TPD, with a per-capita generation of 0.43 kg/day (Sharma et al. 2018a) and a collection efficiency of 60%. The collected waste is disposed of in an open landfill. The study locations are shown in Fig. 1.

Materials and Methodology

Sampling Procedure

The sampling process adopted in the study was according to the guidelines prescribed in ASTM D5231-92 (ASTM 2008). MSW was collected from transporting vehicles at the time of unloading the waste at the dumping sites. Around 1,000 kg of waste samples were unloaded from the transportation vehicles, including trucks, tippers, and so on, on a daily basis. The material was then spread on a plastic sheet, and all the municipal solid waste was mixed using a shovel in order to obtain a homogeneous mixture of the solid waste sample. Out of 1,000 kg of total municipal solid waste dumped daily, 100 kg of waste samples were extracted randomly throughout each day of the 10-day sampling period in order to acquire representative solid waste samples. In the sampling procedure, a total of 40 samples ($n = 10$ for each of the four sites) were employed for the study. The solid waste samples thus obtained from the sampling process were segregated and sorted manually into different components with the help of rag pickers and workers hired by the respective municipal councils of the study regions.

Further, the determination of the density of waste is essential for the design of an effective waste management system. Density plays an important role in the design of engineered sanitary landfills (Sethi et al. 2013). Efficient operation of landfills requires compaction of the waste to optimum density after the placement of waste. Changes in the density may occur as the waste moves from the source to the dumping site due to handling, wetting, drying by weather, and vibrations in the transportation vehicles. The apparatus used for density determination is a wooden box of 1 m^3 capacity and a spring balance weighing up to 50 kg. The municipal solid waste was collected from different parts of the heap of waste to obtain a composite sample. The wooden box of capacity 1 m^3 was placed, and the composite municipal solid waste was poured into the box. The box was filled up to the top and compacted properly. After compaction, the sample was weighed with the help of the spring balance. The waste was placed in the box three times; hence, the average reading is noted. The mass per cubic meter was obtained and the density of the MSW was calculated [ASTM E175 1109-86 (ASTM 1996)].

For the chemical characterization study, about 2 kg of the mixed homogeneous organic fraction was laid out to cover an area of 10 m^2 from which 10 samples of 2 kg were randomly sampled. Further, these 10 samples were completely mixed to obtain a final representative sample of 2 kg, which was then transported to the laboratory in tight plastic bags for chemical analysis including proximate, ultimate, and heavy metal analysis (Mboowa et al. 2017). The process was repeated for all three study seasons to account for any possible seasonal variation at the study locations.

Physical Characterization of Municipal Solid Waste

Information and data on the physical composition of solid wastes are important because they help in determining the selection and operation of equipment, waste to energy (WTE) facilities for energy recovery, and disposal facilities. In this context, waste composition, moisture content, and waste density are important factors because they affect the extent and rate of degradation of waste. For physical characterization of the wastes, the samples were sorted into different components, including biodegradable items, nonbiodegradable items, recyclable items, and inert materials. Then, the sorted materials were segregated into different components, including organics or compostables, paper, plastic, leather, textile, metal, rubber, inert materials, and so on. The weight of individual components was obtained and their respective proportions identified, and the waste samples were immediately transported for moisture content quantification.

Chemical Characterization of Municipal Solid Waste

Solid wastes are complex in nature; hence, knowledge of the chemical characterization of solid waste is mandatory for proper and better understanding of the behavior of waste. In the chemical characterization study, proximate, ultimate, and heavy metal analyses were carried out. The proximate analysis consisted of the determination of ash content, volatile matter, moisture content, and fixed carbon, whereas the ultimate analysis involved the determination of crustal elements like carbon, hydrogen, nitrogen, sulfur, and oxygen content. Samples for the determination of different components of moisture content, volatile matter, and ash content were prepared per ASTM guidelines and as reported in other literature (Mboowa et al. 2017). Fixed carbon was determined as the remaining fraction after the determination of the other different physical components (100-MC-VM-Ash content). The ultimate analysis of the samples was prepared per the guidelines specified in ASTM D3176-09. The organic samples were dried at 105°C for 3 hours, following which they were allowed to cool in desiccators and then ground into powder form, which was then placed in the CHNS analyzer (PerkinElmer, Waltham, Massachusetts) to determine the elemental compositions [ASTM D1102 (ASTM 2013a); ASTM D3176 (ASTM 2002); ASTM E872 (ASTM 2013b); ASTM D5198 (ASTM 2003)]. Oxygen content was determined as the difference because the mineral composition was known. Similar methodology has also been reported in earlier studies (Sethi et al. 2013; Rana et al. 2018; Mboowa et al. 2017; Das and Bhattacharyya 2013).

The calorific and heating values were quantified using an autobomb calorimeter in the laboratory using the methodology reported in the literature (Sethi et al. 2013; Rana et al. 2018; Mboowa et al. 2017). The amount of heat generated from combustion of a unit weight of the sample was expressed in kcal/kg. Heavy metals were analyzed using an atomic absorption spectrophotometer (GBC, model Avanta, Lake Zurich, Illinois). The samples were preprocessed by digesting them in concentrated HNO_3 per the procedure mentioned in ASTM standard D5198-09 (Method A) (ASTM 2003).

Sampling and Estimation of Methane Gas Emission

Methane Generation in Anaerobic Conditions

Estimation of methane gas emission is an important factor in proper management of waste because methane, being a source of green houses gases (GHGs), is of great concern if allowed to escape unabated (Nakibuuka et al. 2012). However, if enough methane is generated, it can be harnessed as a green fuel.

In this context, potential for methane generation was determined from all the study locations over the three seasons. Sample preparation included 30 g of organic waste collected from each of the four respective dumpsites of the study regions. These samples were then transferred into a digester with a capacity of 250 mL, and 50 mL of distilled water was added in the digester to make the total volume 300 mL. The samples were maintained at room temperature and analyzed for methane gas generation after the completion of the digestion process (Mboowa et al. 2017).

Once the digestion procedure was completed, the methane gas generated was extracted using syringes collecting gas sample volumes of 10 μl from the plastic bottle and injected into gas chromatography (GC, Shimdzu, PerkinElmer) using a Supelco-Carboxen TM 1000 column using gas standards and further fitted with a flame ion detector (FID) for the estimation of methane gas generation from the organic waste (Mboowa et al. 2017). The analytical conditions maintained at the FID detector were a temperature of 200°C with sample volume of 1 mL, and the oven temperature was maintained at 120°C. This experiment was repeated three times for each of the organic waste samples, and the average values were noted.

Results and Discussion

Physical Characterization

Physical composition of solid waste often varies depending on the types and sources of MSW. In principle, the nature of deposited waste in the landfill will consequently affect gas and leachate production, composition, and moisture content by virtue of relative proportions of degradable and nondegradable components. The result of physical characterization for all three seasons at all of the study locations in Himachal Pradesh is shown in Tables 1–3, and the composition of the physical characterization of the study regions is illustrated in Figs. 2–5.

It is observed from the tables that at all study locations, the organic waste constituted the highest fraction of the total MSW generated. Organic waste is mainly composed of kitchen waste, including vegetables, food remains, fruit, and materials disposed of from the nearby farmer's market (*sabzi mandi*) and from side stream sources. The average value of organic waste over the three seasons at the study locations was reported to be 55.35% (Solan), 54.20% (Mandi), 51.87% (Sundernagar), and 50.40% (Baddi). The proportion of organic waste was observed to be slightly higher in Solan and Mandi in comparison to other study regions because the landfill sites in these two locations are just adjacent to the fruit and

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Table 1. Physical characterization of municipal solid waste in summer season

Parameter	Solan	Mandi	Sundernagar	Baddi
Density (kg/m^3)	552 ± 1.35	540 ± 2.82	512 ± 1.27	487 ± 0.98
Organic waste (%)	57.67 ± 0.52	56.00 ± 0.63	52.83 ± 0.98	50.83 ± 0.75
Paper (%)	17.17 ± 0.75	18.17 ± 0.75	20.83 ± 0.75	11.50 ± 0.55
Plastic (%)	6.49 ± 0.55	6.33 ± 0.82	6.67 ± 0.52	13.67 ± 0.82
Glass (%)	3.33 ± 0.52	3.17 ± 0.55	3.17 ± 0.41	3.17 ± 0.41
Metal (%)	1.67 ± 0.53	2.17 ± 0.55	2.16 ± 0.75	2.00 ± 0.63
Inert (%)	5.67 ± 1.68	6.00 ± 0.52	6.00 ± 0.63	9.00 ± 0.89
Rubber (%)	2.67 ± 0.52	3.17 ± 0.41	3.17 ± 0.75	1.83 ± 0.41
Textile (%)	5.33 ± 2.67	4.99 ± 0.52	5.17 ± 0.75	8.00 ± 0.63

Table 2. Physical characterization of municipal solid waste in rainy season

Parameter	Solan	Mandi	Sundernagar	Baddi
Density (kg/m^3)	524 ± 2.74	520 ± 4.86	492 ± 2.15	480 ± 2.33
Organic waste (%)	55.00 ± 0.71	54.60 ± 1.54	51.14 ± 0.56	50.40 ± 0.55
Paper (%)	18.80 ± 1.30	17.00 ± 1.87	19.60 ± 1.52	10.60 ± 0.89
Plastic (%)	4.20 ± 0.84	7.40 ± 1.52	5.26 ± 0.71	14.40 ± 1.67
Glass (%)	2.60 ± 0.55	3.20 ± 1.30	2.80 ± 0.81	2.20 ± 0.45
Metal (%)	3.20 ± 0.84	2.80 ± 0.84	3.80 ± 0.45	3.40 ± 0.89
Inert (%)	7.00 ± 0.71	6.80 ± 0.84	7.80 ± 0.45	8.60 ± 1.34
Rubber (%)	3.20 ± 0.84	2.20 ± 0.84	2.80 ± 0.85	2.60 ± 0.89
Textile (%)	6.00 ± 1.22	6.00 ± 1.22	6.80 ± 0.84	7.80 ± 0.84

Table 3. Physical characterization of municipal solid waste in winter season

Parameter	Solan	Mandi	Sundernagar	Baddi
Density (kg/m^3)	514 ± 4.92	490 ± 2.69	482 ± 1.26	465 ± 3.32
Organic waste (%)	53.40 ± 0.55	52.00 ± 1.14	50.40 ± 0.55	49.00 ± 0.71
Paper (%)	12.20 ± 1.10	17.00 ± 1.87	17.80 ± 01.10	8.40 ± 0.55
Plastic (%)	4.60 ± 0.89	7.40 ± 1.52	4.40 ± 0.55	16.40 ± 1.14
Glass (%)	6.60 ± 0.55	3.20 ± 1.30	6.30 ± 0.84	5.00 ± 0.71
Metal (%)	3.80 ± 0.84	2.80 ± 0.84	5.00 ± 0.71	2.80 ± 0.84
Inert (%)	8.00 ± 0.71	6.80 ± 0.84	6.90 ± 0.89	7.80 ± 0.84
Rubber (%)	3.80 ± 0.84	2.20 ± 0.84	2.70 ± 0.84	1.80 ± 0.84
Textile (%)	7.60 ± 0.55	8.60 ± 1.22	6.50 ± 1.00	8.80 ± 1.30

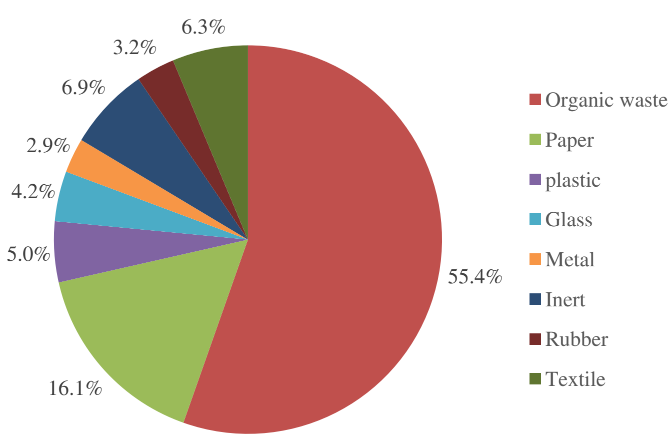

Fig. 2. Percentage of composition of MSW in Solan.

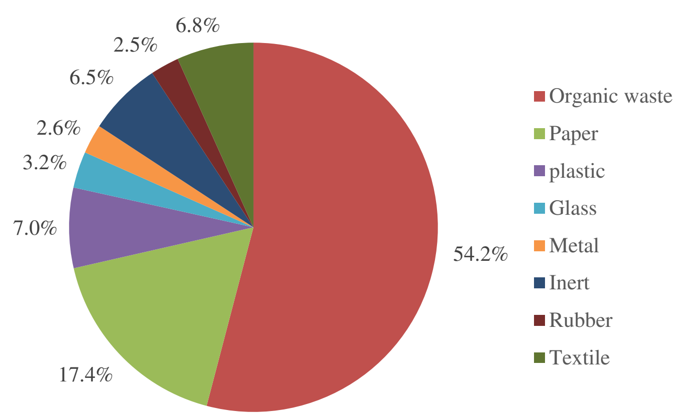

Fig. 3. Percentage of composition of MSW in Mandi.

vegetable markets of the cities and rotten or poor-quality food products are directly disposed of in these dumpsites.

The seasonal variation in the physical characterization of solid waste revealed that organic waste is found more in summer and less in winter due to the high temperature and consumption of more goods, fruits, and vegetables in summer season. An influx of tourists during the summer season may also be a cause of the increased fraction during the summer season. A comparison of

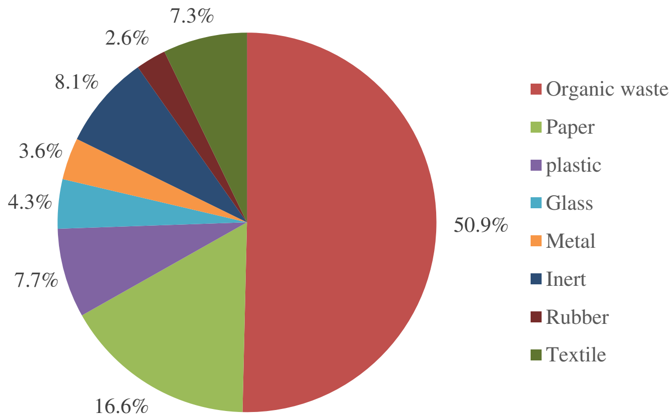

Fig. 4. Percentage of composition of MSW in Sundernagar.

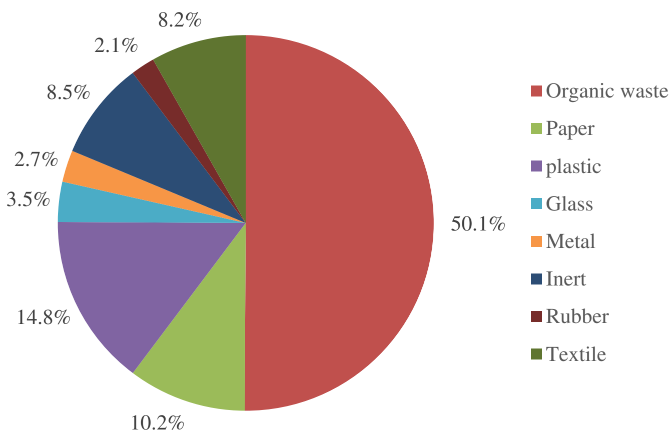

Fig. 5. Percentage of composition of MSW in Baddi.

the results of the physical characterization at the study locations shows agreement with most literature related to South Asian region and also displayed a higher organic fraction of waste in comparison to other similar studies in Indian cities like Jalandhar (33%), Varanasi (31%), Bhopal (40%), Kolkata (50%), Chandigarh, Mohali, and Panchkula (42–53%) with high moisture content (Sethi et al. 2013; Srivastva et al. 2014; Das and Bhattacharyya 2013; Katiyar et al. 2013).

Paper and paperboard formed the second highest fraction out of the total municipal solid waste generated and included all forms of paper products (printed or plain paper, notebooks, newspapers, and magazines) in the study regions of Himachal Pradesh. The average values were determined to be 16.05%, 17.39%, 19.74%, and 10.60% for Solan, Mandi, Sundernagar, and Baddi. The highest reported fraction was in Sundernagar because it is an educational hub consisting of a large number of schools, colleges, institutions, offices, and so on contributing a large proportion. The proportion of paper waste was determined to be greater in summer than in the other two seasons, whereas this proportion showed a slight increase for Solan in the rainy season. In the study locations, because of severe winter conditions, schools and other educational institutions function throughout the summer with more vacation time in winter, which may lead to increased generation of paper products during the summer season. Similar values were reported for characterization studies carried out in nearby tricity region of Chandigarh, Mohali, and Panchkula (15%–17%) (Rana et al. 2018).

The average proportion of plastic in the study regions varied in the range between 5% and 15%. The study revealed that of four towns, the fraction of plastic waste for the Baddi region was on the higher side (almost three times the average of other study locations) and showed progressive increase in seasonal variations. Although the use of plastic carry bags and pouches has been banned in Himachal Pradesh since 2003, the location of the study area is such that it lies in the border regions of Himachal Pradesh and Haryana state, where the use of plastics is still practiced today, thereby leading to an excess fraction in the study location. A comparison with the reported literature showed the fraction of plastic waste in Chandigarh (7%), Jalandhar (9%), and Bhopal (10%) was less than in Baddi but more than in the other study locations of Himachal Pradesh. These fractions should be recycled to reduce transportation costs and increase the lifespan of the dumpsites.

The fraction of inert waste and textile waste was observed to be in the range of 5%–9% in the study regions of Himachal Pradesh. Interestingly, Baddi has a higher proportion of inert and textile waste because of more construction and industrial activities in the town. The fraction of metallic objects and glass bottles was observed to be less at all dumpsites because informal recycling of these by rag-pickers serves as an extra source of income for them.

The two-way ANOVA test is applicable in the results of the physical and chemical characterization of municipal solid waste from four different study regions in Himachal Pradesh. The ANOVA test proves helpful for the analysis of variance of different parameters. The two-way ANOVA test revealed that there was a significant difference in the different parameters of physical characterization when the organic fraction at all the study locations was significantly ($p < 0.001$) in greater proportions than the other physical components like paper, plastics, glass, metal, and so on. However, no significant ($P > 0.05$) variation was observed in metal, glass, textiles, and rubber at the four study locations.

Chemical Characterization

The study of chemical characterization of the MSW samples is to develop alternative treatment strategies and implementation of WTE strategies like biomethanation, refuse-derived fuel, vermicomposting, and similar such technologies and to observe chemical and biological actions. The results of chemical characterization including both proximate and ultimate analysis based on seasonal variation for all the study locations are shown in Tables 4–6.

The moisture content of MSW for the study locations was observed to be high for all seasons, primarily due to a high fraction of organics present in the waste samples. The average range of moisture content of solid waste samples varied from 42% to 51% over the three seasons at all study locations. No significant variation in moisture content was observed over the seasonal analysis at the study locations. The reported literature study revealed lower moisture content for different cities including Bhopal (28%), Chandigarh (35%–59%), and Jalandhar (25%–34%) (Sethi et al. 2013; Srivastva et al. 2014; Das and Bhattacharyya 2013; Katiyar et al. 2013). Moisture content increases the weight of solid waste thereby increasing collection and transportation costs.

The average value of volatile matter in the study regions varied in the range of 23%–28%, which is similar to the volatile matter concentrations reported (17%–28%) for the tricity regions of Chandigarh, Panchkula, and Mohali (Rana et al. 2015) and also for Jalandhar city (18%–25%) (Sethi et al. 2013), which lies in the northern part of India. Seasonal analysis carried out showed that the maximum volatile content was obtained during summer. These values are reportedly significantly less than the volatile fraction reported for Dhanbad city, which is in the eastern part of the country and for which the values lie between 45.28% and 56.72% (Mboowa et al. 2017). The volatile content of the MSW in solid waste is due

Table 4. Chemical characterization of municipal solid waste in summer season

Parameter	Unit	Solan	Sundernagar	Mandi	Baddi
		Proximate analysis of municipal solid waste			
pH	—	6.78 ± 0.37	6.23 ± 0.92	6.57 ± 0.18	5.78 ± 0.52
Moisture content	% by wet weight	51.00 ± 0.66	44.00 ± 1.00	48.00 ± 0.33	43.00 ± 2.67
Ash content	% by dry weight	21.32 ± 0.58	22.22 ± 0.58	24.67 ± 1.53	25.00 ± 2.00
Volatile matter	% by dry weight	26.00 ± 1.00	30.20 ± 1.00	24.00 ± 1.00	28.67 ± 0.58
Fixed carbon	% by dry weight	1.68 ± 0.58	3.58 ± 0.58	3.33 ± 0.58	3.33 ± 1.84
Calorific value	(kcal/kg)	$2,359 \pm 142.34$	$2,528 \pm 272.02$	$2,429 \pm 126.56$	$2,598 \pm 36.86$
		Ultimate analysis of municipal solid waste			
Carbon	% by dry weight	39.95 ± 1.98	38.34 ± 0.88	42.40 ± 1.31	46.83 ± 1.27
Nitrogen	% by dry weight	1.29 ± 0.11	1.18 ± 0.22	2.01 ± 0.07	1.78 ± 0.06
Hydrogen	% by dry weight	4.45 ± 0.45	3.59 ± 0.38	4.07 ± 0.16	5.21 ± 0.77
Potassium	% by dry weight	0.70 ± 0.10	0.80 ± 0.10	0.73 ± 0.06	0.83 ± 0.06
Phosphorus	% by dry weight	0.61 ± 0.04	0.29 ± 0.01	0.35 ± 0.02	0.83 ± 0.12
Sulfur	% by dry weight	0.18 ± 0.02	0.22 ± 0.02	0.19 ± 0.01	0.25 ± 0.01
Oxygen	% by dry weight	12.30 ± 0.67	14.38 ± 1.25	12.23 ± 0.83	10.27 ± 0.03
Mineral content	% by dry weight	40.60 ± 2.08	41.20 ± 4.26	38.03 ± 0.67	34.02 ± 1.49
C:N	—	28.37 ± 0.67	21.13 ± 1.22	25.27 ± 0.55	30.13 ± 1.07

Table 5. Chemical characterization of municipal solid waste in rainy season

Parameter	Unit	Solan	Sundernagar	Mandi	Baddi
		Proximate analysis of municipal solid waste			
pH	—	6.62 ± 0.27	6.18 ± 1.29	6.32 ± 0.76	6.12 ± 0.35
Moisture content	% by wet weight	50.00 ± 1.33	43.00 ± 2.34	48.00 ± 1.00	42.00 ± 1.67
Ash content	% by dry weight	23.80 ± 0.33	25.67 ± 0.78	26.59 ± 1.66	30.08 ± 1.33
Volatile matter	% by dry weight	24.28 ± 2.54	28.38 ± 1.33	22.16 ± 1.66	23.65 ± 1.67
Fixed carbon	% by dry weight	1.92 ± 0.66	2.95 ± 0.33	3.25 ± 0.33	4.27 ± 2.34
Calorific value	(kcal/kg)	$2,371 \pm 245.06$	$2,592 \pm 129.00$	$2,458 \pm 67.58$	$2,612 \pm 194.82$
		Ultimate analysis of municipal solid waste			
Carbon	% by dry weight	42.24 ± 1.25	39.05 ± 0.44	47.24 ± 1.33	48.03 ± 1.33
Nitrogen	% by dry weight	1.23 ± 0.67	1.10 ± 0.14	1.49 ± 0.02	1.78 ± 0.04
Hydrogen	% by dry weight	6.01 ± 0.32	4.27 ± 0.52	4.67 ± 0.22	7.91 ± 0.87
Potassium	% by dry weight	0.72 ± 0.25	0.79 ± 0.10	0.82 ± 0.04	0.92 ± 0.03
Phosphorus	% by dry weight	0.67 ± 0.09	0.36 ± 0.08	0.54 ± 0.02	0.95 ± 0.22
Sulfur	% by dry weight	0.20 ± 0.02	0.15 ± 0.02	0.22 ± 0.03	0.29 ± 0.05
Oxygen	% by dry weight	11.39 ± 0.56	12.43 ± 1.78	9.82 ± 0.63	11.04 ± 1.33
Mineral content	% by dry weight	37.54 ± 2.34	41.85 ± 0.92	35.20 ± 2.14	30.62 ± 1.47
C:N	—	30.21 ± 1.07	23.73 ± 1.33	26.41 ± 0.33	32.02 ± 1.33

Table 6. Chemical characterization of municipal solid waste in winter season

Parameter	Unit	Solan	Sundernagar	Mandi	Baddi
		Proximate analysis of municipal solid waste			
pH	—	6.69 ± 0.67	6.12 ± 0.16	6.27 ± 0.28	5.98 ± 0.61
Moisture content	% by wet weight	48.00 ± 1.33	42.00 ± 2.82	44.00 ± 4.26	40.00 ± 1.66
Ash content	% by dry weight	25.28 ± 0.66	27.92 ± 1.33	28.48 ± 2.67	31.57 ± 3.19
Volatile matter	% by dry weight	24.60 ± 2.33	26.83 ± 1.68	23.60 ± 4.12	23.57 ± 1.67
Fixed carbon	% by dry weight	2.12 ± 0.33	3.25 ± 0.98	3.92 ± 0.56	4.86 ± 0.33
Calorific value	(kcal/kg)	$2,327 \pm 82.68$	$2,620 \pm 161.30$	$2,542 \pm 98.53$	$2,667 \pm 246.89$
		Ultimate analysis of municipal solid waste			
Carbon	% by dry weight	43.82 ± 2.11	41.74 ± 0.65	48.58 ± 1.73	49.36 ± 1.67
Nitrogen	% by dry weight	1.18 ± 0.33	1.04 ± 0.33	1.33 ± 0.02	1.62 ± 0.89
Hydrogen	% by dry weight	7.89 ± 1.03	6.83 ± 0.77	5.67 ± 0.33	8.54 ± 1.02
Potassium	% by dry weight	0.79 ± 0.33	0.91 ± 0.33	0.88 ± 0.33	0.97 ± 0.03
Phosphorus	% by dry weight	0.82 ± 0.33	0.42 ± 0.06	0.71 ± 0.02	0.99 ± 0.33
Sulfur	% by dry weight	0.32 ± 0.02	0.12 ± 0.06	0.34 ± 0.43	0.45 ± 0.33
Oxygen	% by dry weight	13.04 ± 1.28	12.36 ± 0.94	10.41 ± 0.34	9.06 ± 1.22
Mineral content	% by dry weight	32.14 ± 2.32	36.58 ± 2.68	32.09 ± 1.02	29.0 ± 0.54
C:N	—	31.83 ± 1.84	26.89 ± 1.67	28.02 ± 1.67	33.93 ± 2.83

to the presence of biodegradable matter in the solid waste, and the content of volatile matter is indicative of the amount of heat energy that can be produced from the municipal solid waste (Pichtel 2014).

The overall ash content of the waste of in the study locations varied within the range of 23% to 29%, which is significantly less than that reported for Jalandhar (38%–47%) (Sethi et al. 2013) but was similar to the ranges reported for the tricity regions of Chandigarh, Panchkula, and Mohali (22%–35%) (Rana et al. 2018) and Dhanbad city (24.71%–31.69%) (Mboowa et al. 2017). The ash content was observed to be highest for winter conditions at all of the study locations. This is primarily because people in these locations burn wood for heating purposes during the winter. The ash content is significantly influenced by inert materials, and because the inert fractions in the study locations are relatively low, the ash content was not exceeded. As per USEPA recommendation, MSW with ash content between 5% and 15% is suitable for incineration (USEPA 2014).

The value of fixed carbon in the study locations varied in the range of 1.68% to 4.86%. Seasonal variations showed that the proportion of fixed carbon at all the study locations was highest during the winter season due to wood burning, which acts as source of heat during winter. The lowest average value of fixed carbon was observed for Solan, and the highest value was observed for Baddi, and these are correlated to moisture content, which was the highest for Solan and lowest for Baddi. The high value of fixed carbon is indicative of a longer retention time in the combustion chamber to reach complete combustion. Further, a higher value of fixed carbon is indicative that the waste is resistant to aerobic or anaerobic degradation (Lee and Hauffman 2000). Reported literature revealed higher values of fixed carbon of 1.0% to 7.6% for Chandigarh, Panchkula, and Mohali and 6.7%–8.3% for Jalandhar city (Rana et al. 2018; Sethi et al. 2013) in comparison to our study locations.

The average calorific values of the fuel over the three seasons at the study locations were observed to be within the ranges of 2,327–2,667 kcal/kg. The average calorific value for Solan was determined to be the lowest, whereas the highest vale was observed for the Baddi region. This is because although the MSW had the highest moisture content in Solan, it was the lowest for Baddi, thereby affecting the calorific value of fuel. The prevalence of a higher moisture content in the MSW caused a tendency to reduce the calorific value of the waste. Seasonal variation showed that there was a very slight increase but insignificant change (about a 1%–2% increase) in the calorific value of MSW in winter in comparison to summer. Comparison with the reported literature showed that the calorific value of MSW generated in Kolkata (2,717 kcal/kg) (Das and Bhattacharyya 2013), the tricity regions of Chandigarh (2,208 kcal/kg), Mohali (2,508 kcal/kg), and Bhopal (2,412 kcal/kg) were comparable to the results obtained from our study locations. However, calorific values were reported to be significantly higher for the metropolitan cities of Mumbai (7,477 kcal/kg) and Delhi (4,498 kcal/kg). The calorific values obtained for our study locations suggest it is suitable for energy recovery.

The average value of carbon content was reported in the range of 39% to 49% in the study region of Himachal Pradesh primarily due to the presence of a high fraction of organic contents in the municipal solid waste. The highest value of carbon content was reported during winter months because of more consumption of fruits and vegetables in winter seasons. Comparison with the reported literature showed similar trends for studies carried out in an Indian context (Sethi et al. 2013; Rana et al. 2018; Mboowa et al. 2017).

The average composition of the nitrogen content was determined to be 1.23% for Solan, 1.11% for Sundernagar, 1.61% for Mandi, and 1.73% for Baddi, indicating very low proportions. The maximum fractions of nitrogen occurred during summer. Comparison with the reported literature showed that the nitrogen fraction was slightly more than that observed in Kolkata (Das and Bhattacharyya 2013) but within the ranges as observed in Chandigarh (Rana et al. 2018), Jalandhar (Sethi et al. 2013), and Dhanbad (Mboowa et al. 2017). Potash, phosphorous, and sulfur content were observed in trace fractions with the average variations within the ranges of 0.74% to 0.91%; 0.36% to 0.92%; and 0.16% to 0.33%, respectively. The maximum fractions were observed to be in the Baddi region due to its being an industrial area. Seasonal variation showed a slight increase but insignificant change in the winter season. Comparative analysis with the reported literature showed phosphorous proportions similar to those reported for Kolkata (Das and Bhattacharyya 2013), whereas the potash values were slightly greater than those in Kolkata and similar to those reported for Bhopal (Katiyar et al. 2013). Nitrogen and phosphorous together constitute between 1.5% and 2% at all the study locations and are similar to the values reported for other study locations (Sethi et al. 2013).

The C:N ratio was found to be in the range of 23.92 to 33.03 in the study locations, indicating its suitability for the composting process (Sethi et al. 2013; Rana et al. 2018; Mboowa et al. 2017). The average values of C:N obtained were 30.14 for Solan, 23.92 for Sundernagar, 26.56 for Mandi, and 32.04 for the Baddi region of Himachal Pradesh. Seasonal analysis showed slight but insignificant variation for the C:N ratio up to the winter season. Studies conducted on the C:N ratio of waste revealed almost the same characteristics in some of the Indian cities; that is, it varied within the range of 20 to 40, indicating that the MSW generated is amenable to composting (Sethi et al. 2013; Srivastva et al. 2014; Das and Bhattacharyya 2013; Katiyar et al. 2013).

It is important to determine the heavy metal concentration present in MSW because their presence may harm the digestion process of waste. The result of heavy metals based on seasonal variation is shown in Tables 7–9 for the study locations. The analysis of heavy metals for the study locations revealed that the

Table 7. Heavy metal analysis of municipal solid waste in summer season

Parameter	Solan	Mandi	Sundernagar	Baddi	Permissible limits (Mandal et al. 2014)
Cadmium	0.78 ± 0.33	0.63 ± 1.76	0.56 ± 0.05	0.89 ± 0.66	5.00
Chromium	39.85 ± 1.68	28.47 ± 0.33	19.93 ± 1.67	58.05 ± 0.85	50.00
Copper	30.06 ± 0.89	21.53 ± 0.67	14.62 ± 4.66	43.12 ± 1.67	300.00
Iron	2,304.69 ± 16.87	2,218.57 ± 14.67	1,894.39 ± 32.15	4,135.06 ± 22.46	—
Manganese	26.89 ± 6.83	20.67 ± 2.33	17.69 ± 1.78	32.36 ± 6.87	—
Nickel	21.82 ± 0.33	11.86 ± 1.67	9.89 ± 1.67	34.12 ± 2.33	50.00
Lead	16.43 ± 0.67	7.56 ± 0.67	11.28 ± 1.33	29.48 ± 1.67	100.00
Zinc	34.87 ± 2.56	27.04 ± 0.38	29.25 ± 5.25	42.92 ± 2.62	1,000

Note: All units are mg/kg.

Table 8. Heavy metal analysis of municipal solid waste in rainy season

Parameter	Solan	Mandi	Sundernagar	Baddi	Permissible limits (Mandal et al. 2014)
Cadmium	0.71 ± 0.04	0.78 ± 1.08	0.61 ± 0.05	1.06 ± 0.06	5.00
Chromium	42.34 ± 0.54	23.43 ± 2.32	27.51 ± 1.52	72.89 ± 3.79	50.00
Copper	38.90 ± 0.72	30.05 ± 0.78	22.52 ± 1.94	57.84 ± 1.25	300.00
Iron	$2{,}418.70 \pm 12.76$	$2{,}352.86 \pm 12.65$	$2{,}072.05 \pm 47.15$	$4{,}641.06 \pm 22.46$	—
Manganese	29.45 ± 3.12	24.43 ± 0.06	18.29 ± 1.62	37.12 ± 4.75	—
Nickel	26.31 ± 0.57	17.21 ± 1.04	10.00 ± 1.62	45.15 ± 0.85	50.00
Lead	19.16 ± 0.78	9.24 ± 0.43	14.52 ± 0.75	34.92 ± 8.69	100.00
Zinc	39.28 ± 1.92	31.20 ± 0.75	36.78 ± 4.52	47.00 ± 1.64	1,000.00

Note: All units are mg/kg.

Table 9. Heavy metal analysis of municipal solid waste in winter season

Parameter	Solan	Mandi	Sundernagar	Baddi	Permissible limits (Mandal et al. 2014)
Cadmium	0.84 ± 0.07	0.74 ± 1.23	0.68 ± 0.34	0.90 ± 0.07	5.00
Chromium	49.83 ± 1.25	26.65 ± 1.85	21.67 ± 1.82	81.43 ± 1.95	50.00
Copper	40.24 ± 2.63	37.83 ± 0.92	24.91 ± 1.25	66.81 ± 1.75	300.00
Iron	$2{,}498.03 \pm 11.69$	$2{,}374.24 \pm 16.91$	$2{,}179.09 \pm 39.16$	$4{,}721.09 \pm 25.82$	—
Manganese	54.52 ± 2.64	26.39 ± 2.83	39.18 ± 1.72	82.32 ± 6.82	—
Nickel	27.24 ± 0.76	19.22 ± 1.53	16.84 ± 1.42	31.62 ± 1.95	50.00
Lead	21.82 ± 0.75	9.91 ± 1.45	15.83 ± 0.76	39.81 ± 4.21	100.00
Zinc	42.65 ± 2.12	35.92 ± 2.57	32.21 ± 5.63	51.72 ± 1.92	1,000.00

Note: All units are mg/kg.

concentrations were found to be within the permissible limits and hence suitable and safe enough to be applied as compost. The dumpsite of Baddi had a higher concentration of chromium and iron content because of the tendency toward industrial and pharmaceutical activities in the town. To elaborate further, large concentrations of Fe were determined at all four study locations in Himachal Pradesh. The higher concentration of iron in municipal solid waste can be attributed to steel scraps and other such materials being disposed of in huge quantities in the uncontrolled or open dumping sites of the respective regions. Hence, lack of proper segregation of waste is one of the main reasons of the presence of heavy metals in the waste. Further, it is observed that of the four study regions, Baddi has the highest concentration of Fe because it is the industrial area of Himachal Pradesh wherein certain fractions of industrial solid waste also get mixed with domestic MSW at open dumpsites, thereby leading to possible increased Fe concentrations.

The two-way ANOVA test for chemical characterization revealed a significant difference ($P < 0.001$) existed been the different parameters analyzed for proximate and ultimate analysis, but there was no significant difference ($P > 0.05$) among these parameters at the study locations in Himachal Pradesh.

Landfill Gas Emissions

The monitoring of landfill gas emissions (in particular methane) was evaluated for the MSW disposal site study regions of Himachal Pradesh including Solan, Sundernagar, Mandi, and Baddi by gas chromatography analyzer. The concentration of methane generation was estimated for the study locations over the three seasons and the average concentrations along with the seasonal variation are reported in Table 10.

The average range of the methane generation was determined to be 15.78 for Solan, 14.37 for Mandi, 13.87 for Sundernagar, and 14.37 for Baddi, wherein these values represented ppm of

Table 10. Estimation of methane gas emission

City	Methane generation (ppm methane/g of waste) Summer season	Rainy season	Winter season	Average
Solan	17.02 ± 0.76	16.64 ± 1.98	13.69 ± 0.98	15.78 ± 1.24
Mandi	15.28 ± 1.23	14.79 ± 0.56	13.03 ± 1.45	14.37 ± 1.08
Sundernagar	14.91 ± 0.98	13.72 ± 0.33	12.98 ± 0.86	13.87 ± 0.72
Baddi	12.02 ± 1.02	11.63 ± 0.78	11.05 ± 0.67	14.37 ± 1.08

methane generated per gram of waste. These values concurred with the literature, wherein a study at Dhanbad concluded that methane emissions from the solid waste were 18.18 ppm methane/gm of waste and 20.08 ppm methane/gm of waste for two different study areas in Dhanbad city (Mboowa et al. 2017). Interestingly, the amount of methane gas generation is directly proportional to organic waste (Kazayuki and Katsuyuki 2012) and inversely proportional to the ash content, as reported by many studies (Sethi et al. 2013; Rana et al. 2018). The highest concentration of methane gas was determined to be in the Solan study area because it has the highest fraction of organics. Seasonal variation showed a slight increase in methane generation during summer and slightly less in winter conditions due to reduced activity of bacterial kinetics.

Municipal Solid Waste Management Plans and Possibilities for Implementation of Different Waste to Energy Technologies Based on Characterization Analysis

This section discusses waste management plans, including proper collection, sorting, and segregation and some of the potential waste-to-energy facilities that can be used at the study locations based on the characterization results obtained. In principle, separation of organic, recyclable, and inorganic fractions is important before deciding on the appropriate WTE facilities to be implemented. Further, the process of implementation of the suitable WTE processes can be done in cluster formation wherein one WTE facility caters to the study locations of Solan and Baddi, whereas the other provides services to the towns of Sundernagar and Mandi due to their closer proximity. The use of the cluster technique was proposed in a feasibility study conducted by the Government of India in association with the Himachal Pradesh State Government for developing a waste-free state in the long term (MoUD 2015).

Collection of Municipal Solid Waste

The existing practices of MSW management in the study locations and the drawbacks associated with them have already been presented and discussed in earlier reported literature (Sharma et al. 2018a). To summarize, it was suggested that generated MSW should be collected using different methods, including the use of central bins, door-to-door collection, collection on a regular basis at preinformed timings, and other such coordinated activities. Roadside underground and semiunderground dustbins should be provided for primary collection of waste bins at a distance of 80–100 m from residential locations. In this context, underground waste collection bins of adequate capacities should be provided because they may provide better aesthetics and prevent bad odors emanating from the stored underground bins dispersing to the atmosphere. A similar proposal was also made in the feasibility study conducted for the state (MoUD 2015). The underground bin collection system also provides a secured system with no overflow of waste bins to the surface, thereby avoiding any stray animals feeding on them. The installation of underground waste bins should be provided at 100-m distances in the cluster of individual regions with geographic information systems (GIS) mapping, and a web-based monitoring system of installed waste collection bins has proved beneficial. Scheduling of the smart waste monitoring and collection system includes waste containers including transmitters and sensors. The sensor is placed near the top of the waste container and hence used to sense the waste fill level. The signal is transferred by means of the transmitters only when the waste bins are filled up to a specific level or mark, and the signal produced by the sensor is received by the receiver at a central station (Hassan et al. 2016). The central system will then send a message to the vehicle operators to go where the bins are located to empty them. This web-based monitoring system has proved beneficial in order to reduce time, cost, and human effort (MoUD 2015).

Sorting and Segregation of Waste

Similarly to the strategy discussed in the previous section, the advantages of the segregation process have already been discussed in an earlier reported study (Sharma et al. 2018a). In this context, sorting and segregation of municipal solid waste proves beneficial at the household level so that waste processing becomes easier. Apart from this, the municipal authority of study regions in Himachal Pradesh has initiated some programs to encourage the initial segregation of municipal solid waste. Urban local bodies (ULBs) are encouraging citizens to keep three separate waste collection bins in their homes to collect organic, recyclable combustible and inert waste. In order to encourage citizens, awareness programs regarding benefits of segregation of waste products should be conducted along with the promotion of recycled products (Sharma et al. 2018b). The segregated waste components shall be transported to recyclers or processing sites, and inert waste must be sent to disposal sites.

Implementation of Different Waste-to-Energy Techniques

Biological Treatment Processes

The physical characterization studies showed that there is a high proportion of organic matter in the waste generated in all of the study locations. Organics are biodegradable in nature and thereby have the capacity to generate energy. In principle, both anaerobic and aerobic processes can be used to treat biodegradable organics. The anaerobic process uses less energy in comparison to the aerobic process and converts the biodegradable fraction into biogas (Fricke et al. 2005), which can be used as green fuel for producing heat or electrical energy. However, in the presence of enough air, the aerobic process works relatively faster, producing finished compost, in comparison to the anaerobic degradation process, which takes more time. Flow charts indicating the preferred pathways or generation of biogas and compost by using the wet fraction and generation of energy using dry waste are shown in Figs. 6 and 7.

Anaerobic Process

In practice, the generation of biogas takes place as a wet or dry process depending on the solid concentrations. The wet technique involves generation of biogas and involves the use of a low solids concentration, whereas dry technology is generally used when the concentration of solids is significantly high. In this context, biomethanation plants are often installed to generate biogas, in which it is often used as green fuel. Biogas is a mix of methane, carbon dioxide, and other gases, but in very small quantities, which can be converted to heat and electricity. The composition of biogas from anaerobic digestion is presented in Table 11 (Petersson 2013).

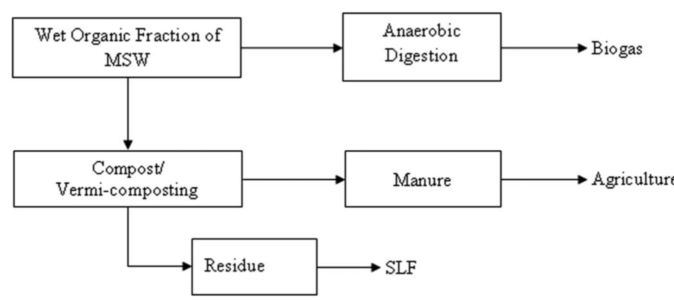

Fig. 6. Pathways for generation of biogas or compost using wet waste.

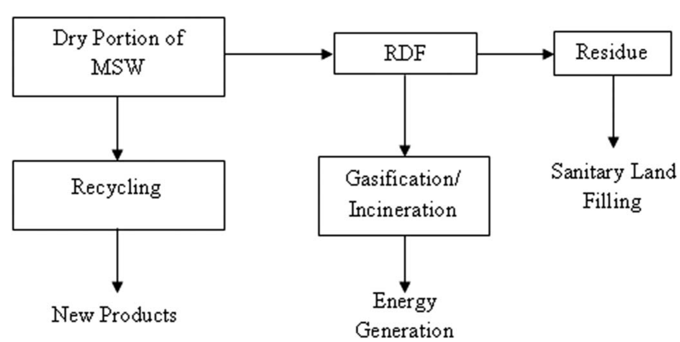

Fig. 7. Pathways for generation of energy and new products using dry waste.

Table 11. Composition of biogas from anaerobic digestion

Compound	Unit	Value
Methane	mol%	50–80
Carbon dioxide	mol%	15–50
Nitrogen	mol%	0–55
Oxygen	mol%	0–1
Hydrogen sulfide	mg/m^3	100–10,000
Ammonia	mg/m^3	0–100
Total chlorine	mg/m^3	0–100
Total fluorine	mg/m^3	0–100

Source: Reprinted from *The Biogas Handbook*, A. Petersson, "Biogas Cleaning," pp. 329–341, © 2014, with permission from Elsevier.

It can be observed from the previous table that biogas contains a huge concentration of methane (50%–80%), making it suitable for energy recovery. The success of the anaerobic process of degradation of waste is governed by different factors, including pH and temperature. Inadequate maintenance of pH leads to generation of volatile fatty acids (VFAs) in the acetogenesis phase, rendering the methanogens ineffective by reducing the pH value (acidic conditions) and thereby leading to less or no production of methane. Further, methanogens involved in the anaerobic process for generating methane gas are particularly effective at mesophilic temperature conditions for biogas production. In this context, it is important to note that our study locations experience very cold temperatures in winter seasons, often lasting up to 3 to 5 months, which could severely affect the methane generation process because the rate of gas production by methanogens is extremely low. In such cases, anaerobic digesters need to be provided with heat jacketing or other systems to counter such temperature conditions. Further details have been discussed elsewhere for adequate provisions for generation of biogas (Sharma et al. 2018a). The advantages and disadvantages associated with methane production at different operating temperatures are presented in Table 12.

Aerobic Process

The physical characterization study of municipal solid waste in Himachal Pradesh revealed that solid waste is rich in organic waste. In this context, composting is a viable option for the decomposition of organic waste (Sharma et al. 2018b). The decomposition and stabilization of organic matter takes place in the process of composting under controlled environmental conditions. Microorganisms feed upon the organic matter and convert the waste into more stabilized products. In this process, the compost generated has good water-holding capacity and acts as a soil conditioner in agricultural activities. Incoming organic waste should be sorted prior to any processing in facilities. Implementation of the pile composting method at the study locations can be done because it is cheap and suitable for all locations (Jouhara et al. 2017).

Composting is an aerobic process that requires proper ventilation and aeration for microorganisms in order to maintain effective decomposition (Arena and Di Gregorio 2013). In this context, the extra amount of ventilation causes a drop in temperature and hence loss of moisture and less aeration to produce excessive moisture, so proper maintenance of ventilation or aeration is the necessary issue in the composting process (Arena and Di Gregorio 2013). In this context, various studies have revealed that pile composting is one of the best ways to process organic waste in terms of economy and ease. Apart from this, a multibin system is also an effective composting method that may be proposed for waste processing in the study regions of Himachal Pradesh. It permits the production of final compost in a much faster manner than the single-bin based composting technique. The working of multibin-based composting is such that the biodegradable material is first put into the new pile and when enough organic waste is collected, material is turned into the next bin to allow faster decomposition, and another pile is started in the discharged bin.

Further, the evaluation and quantification of different fractions of municipal solid waste of four study regions in Himachal Pradesh

Table 12. Advanced anaerobic digestion technologies to produce biogas, their advantages and disadvantages

Anaerobic digestion technologies	Operating temperature	Advantage	Disadvantage
Wet waste	Mesophilic (35°C–40°C) (Malik et al. 2014; Jing et al. 2016)	• Pretreatment method to improve the efficiency of biogas process • Low level of sludge generation • Low operational temperatures • Stable operation	• Less diffusion of the technology • Low investment in facilities • Low government subsidies • Large periods of cultivation
	Thermophilic (55°C–60°C) (Maria et al. 2017; Stamatelatou et al. 2014)	• Production of hydrogen and methane • High organic loading rate • Low operational and maintenance costs • Increased gas production • Resistance to foaming	• Less stable—instability problems • Higher residual volatile acid concentrations • Limited number of digesters
Dry waste	Mesophilic (35°C) (Fernández-Rodríguez et al. 2013; Shi et al. 2013)	• Less accumulation of volatile acids • Lower specific growth rate of microorganisms • Highest organic matter removal rate	• Lower reductions of cellulose and hemicelluloses • A larger operating time to obtain methane and organic matter degradation (40 days)
	Thermophilic (55°C) (Andriamanohiarisoamanana et al. 2017; Kinnunen et al. 2014)	• Greater reductions of cellulose and hemicelluloses • Shorter operating time to obtain methane and organic matter degradation (20 days) • Higher coefficient of methane production. Inhibited due to ammonia with organic loading rate	• Accumulation of volatile fatty acids • Higher specific growth rate of microorganisms

Source: Adapted from Moya et al. (2017).

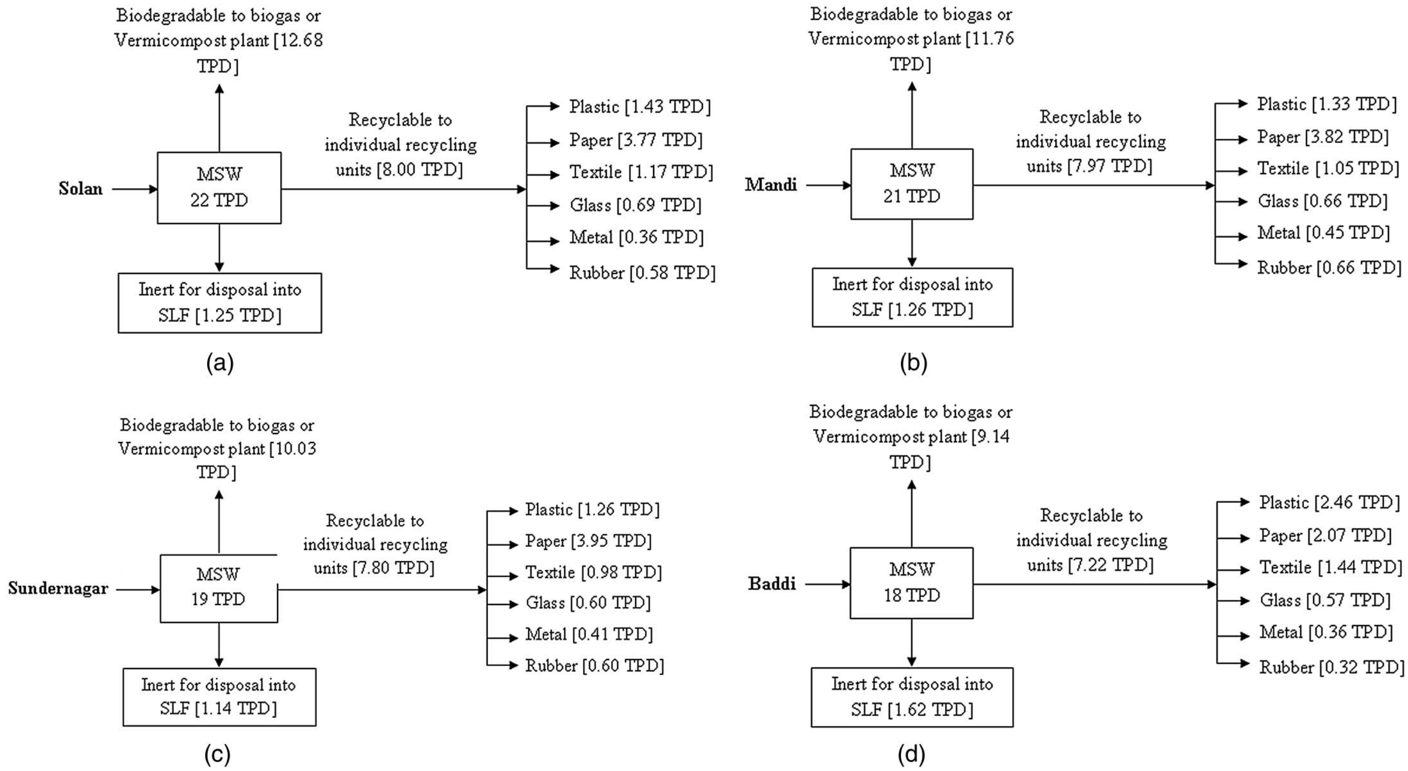

Fig. 8. Quantification of different waste fraction in (a) Solan; (b) Mandi; (c) Sundernagar; and (d) Baddi.

is shown in Fig. 8. It may be stated observing from Fig. 8 that the wet fraction of the organic part of the waste may be used in composting or vermicomposting and the dry fraction of nonbiodegradable items may be transported to recyclers and waste processing units for the recycling process. However, residue may be disposed of in a sanitary landfill for the safe disposal of municipal solid waste.

Vermicomposting

Vermicomposting is a method of converting waste into manure through the activities of earthworms and microorganisms (Rana et al. 2017). Large-scale vermicomposting facilities are already in existence in some of the study areas but are being significantly underused due to lack of trained manpower, lack of information regarding the potential benefits among the population, and improper maintenance of these pits. Another potential drawback as observed from the characterization results is that the wastes have certain fractions of heavy metals that may hinder the use of organic waste for composting; hence, the heavy metals need to be treated before vermicomposting is carried out.

Thermal Treatment Processes

Incineration

The incineration process is one of the most widely used treatment process for disposal of generated MSW. The primary process involves burning waste in a combustion chamber preheated to a temperature around 1,000°C using a combination of flue gas and heated air. After the process has been completed, energy and exothermic heat generated are harnessed using a superheated system in a cogenerated system (Tan et al. 2014). The main drawback in the application of the system is the high emissions of the greenhouse gases (GHGs), which is of significant environmental concern (Ashworth et al. 2014). However, in this context, improved and advanced technological systems are in place to regulate the emissions of such GHGs. The incineration process is also often conjoined with the gasification technique to remove volatile heavy metals (Wu et al. 2014).

Pyrolysis

Pyrolysis is defined as the combustion process in the absence of oxygen. The process involves burning of waste in a heated chamber preset to temperature ranges of 300°C to 800°C. In the initial phase, the organic fraction is decomposed at a temperature of 300°C in an oxygen-free environment, after which the remaining fraction of the MSW is burnt off at 800°C, leading to production of final products. Segregation of waste is an important aspect that needs to be implemented before using this technique to remove the glass, metals, and inert fractions of the waste (Moya et al. 2017). The final expected outproduct is syngas, which mainly consists of CH_4, CO_2, CO, and H_2 with a high calorific value of 20 MJ/Nm^3 (Zafar 2014). Syngas can be used as an energy source for different power applications like running industrial boilers, turbines, and other such heavy power-consuming machinery (D'Alessandro et al. 2013). Pyrolysis can handle both organic and plastic fractions of waste. The process of plasma pyrolysis is the most advanced technology to produce syngas, which transforms plastic waste to a high calorific-value fuel.

Gasification

The main process involved in this technique is partial oxidation, and it has been successfully used to reduce the volume of waste by 90%. Further, a proportion of energy generated is used to drive the process to completion and can work over higher temperature ranges of 700°C to 900°C. The syngas generated could be as a fuel for energy for different industrial applications (Thakare and Nandi 2016). The major associated advantages of using this process are large reduction in mass and volume of waste and thus a lower land requirement for disposal, recycled products segregated, reduced emissions due to advanced technologies, and cogeneration of both heat and electricity (Moya et al. 2017).

Installation of RDF Facilities

Presently, there exists no waste treatment processing facility of municipal solid waste in the study regions of Himachal Pradesh. The installation of a refuse-derived fuel plant is one such feasible option that can be used as a waste-processing facility in the study regions due to the lower proportion of metals and higher fraction of other waste, including paper, rags, plastics, and so on. In particular, organic waste may be separated out and only nonorganic components allowed in the processing of RDF. Presently, there exists only one functional RDF plant in the entire region of North India, and it is located in Chandigarh operating under the name of Green Tech Fuel Processing Plant. The functional working details of the plant have already been reported in detail in a separate study (Rana et al. 2015). However, to summarize, the RDF plant has a capacity to generate RDF with a calorific value of 3,100 kcal/kg with a moisture content of less than 15% and a daily waste intake capacity of 500 TPD (Rana et al. 2015). The calorific value reported for Chandigarh is 2,208 kcal/kg (Rana et al. 2018) and is comparable to the calorific values of MSW for all four study locations in Himachal Pradesh. In this context, similar RDF plant capacity based on the same design principles maybe adopted for the study locations in Himachal Pradesh. Further, as mentioned earlier, two such plants should be constructed such that one plant serves the region of Solan and Baddi and the other serves the region of Sundernagar and Mandi.

Biorefinery

A biorefinery essentially works on the same principle as a petroleum refinery, with one major difference being the use of waste for generation of energy along with generation of biofuels, biofertilizers, and so on (Aracil et al. 2017). The process involves the conversion of MSW into liquid and gaseous fuels. This method is advantageous because the organic fraction can be transformed to biofuels, whereas the inorganic proportion can be changed to a solid recovered fuel (SRF) that can then be further used to produce syngas and hence be a potential source of energy for different industrial applications (Kokossis 2014).

Suitability of the WTE Options Based on the Characterization Results

The average calorific value of MSW generated in India is about 3,350 kJ/kg (Zhu et al. 2008), which is significantly lower than the calorific value ranges of 8,000 to 10,000 kJ/kg required for profitably installing incineration technologies, else additional fuel costs will be incurred. The average calorific value of wastes generated at the study locations varies within the ranges of 2,352 to 2,625 kcal/kg, and the feasibility of using aerobic composting as an alternative treatment means for MSW with these calorific values has also been suggested. The presence of a large organic fraction of the waste significantly reduces the benefits of the incineration process. In such a scenario, an incineration process may not be the optimal solution for the existing study locations.

In this case, the most potent WTE options could be individual use of organic and inorganic fractions by using a biological treatment process and RDF facilities, respectively, or using a biorefinery wherein both the organic and inorganic fractions can be harnessed to generate biofuels and syngas, respectively.

Collection and Use of Landfill Gas Emissions

Landfill gases are generated mainly due to the action of microbes on the degradable fraction of waste. Initially, aerobic conditions are more prevalent; however, with passage of time (about a year), anaerobic conditions are more prevalent, leading to generation of landfill gases. As such, landfill gases primarily consist of methane (60%) and carbon dioxide (40%). Because our characterization studies have shown large fractions of organics in the study areas, it is expected a large proportion of methane gas will be generated. In such a scenario, landfill gas should be extracted using the appropriate methodology (gas extraction wells, construction of

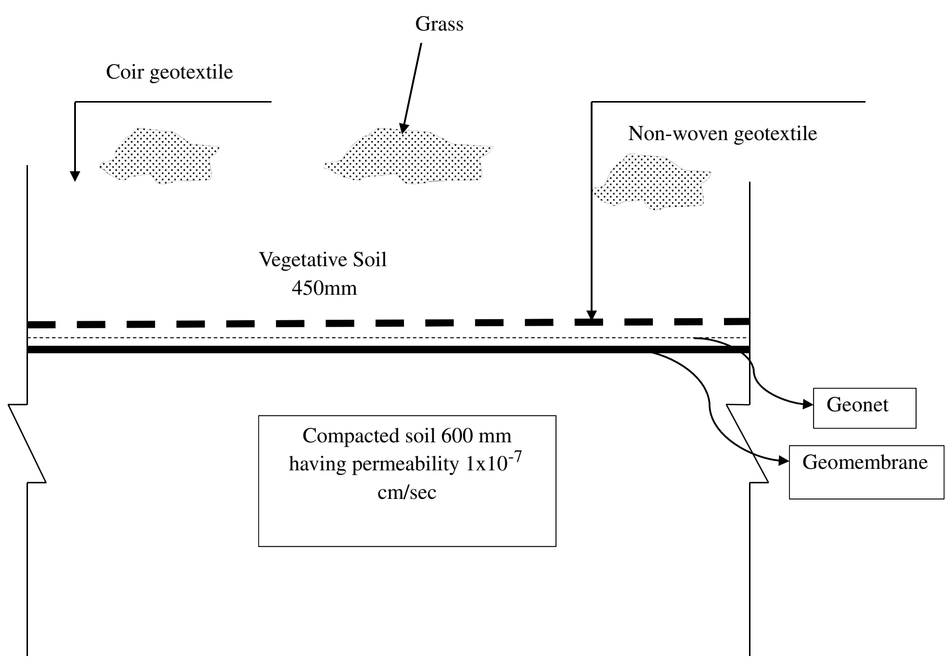

Fig. 9. Capping components of sanitary landfilling system.

horizontal trenches) from the current landfill sites; the collected gas should be properly cleaned to remove impurities, particularly particulate matter, and the methane collected for different energy purposes can be reused.

Engineered Landfill Site

After the process of reuse of the biodegradable, recyclable, and inorganic fractions of the waste, the inert and soil fractions of the MSW generated should be disposed of into sanitary landfills for the period of 25 years. Landfilling shall also be carried out for residues of waste-processing facilities as well as postprocessing rejects from waste-processing facilities. The waste added should be compacted to achieve a density of 0.8–0.85 t/m^3 and capped properly. The closure surface should be provided with a stable slope because it will be the deciding parameter to determine the height of the closure of municipal solid waste. Moreover, this slope will decrease the cutting volume in the closure area and hence increase the filling area of the closure. Apart from this, waste should be covered immediately or at the end of each working day with a minimum thickness of 10 cm soil (Krishna et al. 2015). After the completion of landfill, a final cover should be designed to reduce the migration of leachate and erosion. The final cover should have a barrier soil layer composed of 60 cm of clay with a permeability coefficient less than 1×10^{-7} cm/s (Sharma et al. 2016). On top of the barrier soil layer, there should be a drainage layer of 15 cm and on top of the drainage layer, there should be a vegetation layer of 45 cm to support natural plant and vegetation growth. A schematic of the capping components of a landfill is presented in Fig. 9.

Apart from this, in view of the hilly or mountainous terrain of Himachal Pradesh, it is recommended to construct small or cellular sanitary landfills because such landfills would be easy to operate and close after their use. The space available on top of the closed landfills can be used for other recreational activities, including parking, gardens, and so on. Hence, in a nutshell, landfilling of municipal solid waste is a feasible option for the better disposal of waste.

Conclusion

The characterization analysis of the study regions showed that all locations had a high proportion of organic waste in the MSW generated and hence can act as potential sources of biogas generation. This was also indicated from the C:N ratio observed from the study locations, where this value was in the optimal ranges. A correlation also existed between the fraction of organics and methane gas generated and the determined moisture content. A higher content of the organic fraction implies a higher propensity for methane gas emissions. Chemical characterization analysis showed seasonal variation for some parameters like ash content and fixed carbon due to wood burning for heat purposes during this season. Heavy metal analysis showed that these values currently existed between the limits but may be of concern in the future if no corrective steps are taken because the use of organic material as compost may become restricted. The average calorific value over the study locations were determined to be 2,508 kcal/kg. This is representative of about 61% of energy generated from biomass and about 27% generated from bituminous coal. The average methane generation over the study locations was 14.6 ppm/g of waste, which is significant enough to be harnessed as green fuel. In this context, suitable WTE technologies for the study locations have been proposed and discussed.

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