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Status, characterization, and potential utilization of municipal solid waste as renewable energy source: Lahore case study in Pakistan

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ABSTRACT

With rapid increases in population and urbanization, uncontrolled municipal solid waste (MSW) is a threat to public health and environmental safety. In this study, we explore its generation, treatment, and characteristics of physical/chemical composition and assess the potential of MSW as a renewable energy source in Lahore, the second largest city in Pakistan. Based on the average generation rate of MSW (*i.e.*, 0.65 kg/capita/day), the daily production of MSW in this city would reach 7150 tons/day. However, its disposal in a safely engineered way has been restricted due to the lack of: (a) pre-planning, (b) infrastructure, (c) political will, and (d) public awareness. Various samples of MSW considering socio-economic structure were collected. The physical components of MSW in Lahore were found to be in the descending order of biodegradable, nylon plastic bags, textile, diaper, and paper. The inductively coupled plasma optical emission spectroscopy (ICP-OES) technique was used to determine the heavy metal content and leachability of the MSW components to check for the environmental contamination risk. The proximate and ultimate analysis of this MSW was also carried out along with its heating values. The average high heating value of MSW was measured as 14,490 kJ kg^{-1}. Energy recovery potential of 48 MW was assessed further from 2000 tons of MSW/day. The results of this study should be helpful for policy makers to establish a MSW management strategy for the potential renewable energy alternative.

1. Introduction

The earth is facing various challenges because of the rapid increase in population and urbanization (Nicolopoulou-Stamati et al., 2013; Seik, 1997; Uttara et al., 2012). In this respect, the management of municipal solid waste (MSW) has been recognized as one of the most important elements for sustainable development in the future. The quality (or composition), quantity, and leachates of MSW vary from one region to another. Such variation is generally dependent upon the combined effects of various parameters, such as lifestyle or living standard, socioeconomic levels, local regulations, recycling, and behavior of habitants (Khan et al., 2016; Rong et al., 2017).

MSW can also play a valuable role as a source for electricity production or for reduction of greenhouse gas (GHG) emissions (Cheng and Hu, 2010). Most developed countries have already built management strategies for MSW regarding electricity production. Currently, conventional technologies, such as combustion involving incineration, pyrolysis, and gasification (or generation of combustible fuels including methane and hydrogen), have been extensively employed to produce energy from MSW (Ryu, 2010). Initially, incineration was a well-known technique to reduce the volume of MSW and to protect the environment from hazardous wastes, although it is not for energy recovery (Brunner and Rechberger, 2015a)

In developing countries, the recent advancements in combustion technology and air pollution control systems (APCS) have been suggested as a potential alternative option to pursue a sustainable environment. In particular, incineration is recognized as an attractive and sustainable solution for MSW management. It has also been highlighted as a technique to convert MSW into economically affordable energy sources, as well as to provide products that have the potential for further utilization (Luo et al., 2010). The emissions from incinerators have been reduced to such a low value that the United States Environmental

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Protection Agency (US EPA) has declared MSW incineration as a cleaner source of energy (Bajić et al., 2015; Brunner and Rechberger, 2015b; Leme et al., 2014). However, many of the developing countries have not yet efficiently utilized incineration technologies to date. The main problems confronted during incineration of MSW in developing countries are often designated as the issues associated with high moisture content, low energy content, and variable compositions. According to International Energy Agency, the average calorific value of MSW should be greater than 7942 kJ kg^{-1} for an effective incineration with energy recovery operation (Melikoglu, 2013), whereas such value must be greater than 7100 $kJkg^{-1}$ according to World Bank report (1999). The waste stream of developed countries has high calorific values as compared to the developing countries as the latter is characterized by high percentage of paper, plastic, and textile but low percentage of biodegradables (Chen and Christensen, 2010; Komilis et al., 2014). In this study, we provided an overview of MSW and its management, its physical and chemical characteristics, and its potential as a renewable energy source based on the data collected from an MSW facility located in Lahore, Pakistan.

2. MSW management and characterization

2.1. Generation, challenges, and potential utilization

The population of Pakistan has been increasing annually by 2.4% since 1998 to a record 207.7 million as of 2017, which corresponds to the 6th most populous country in the world. Lahore has been the second largest city in Pakistan, which has grown through a population shift for better sociocultural and economic reasons. Therefore, the MSW facilities have grown drastically in the last few decades. In this study, the Lahore Waste Management Company was selected as a representative MSW treating company, because this company is equipped with the best available infrastructure, facilities, and collection efficiency of MSW in the local area. As all of the major cities in the country concurrently experience the same seasons, the factors controlling the generation of MSW (like geographic locations, industrial status, infrastructure, and socio-culture) are less likely to make any noticeable differences between the cities (Batool and Ch, 2009; Korai et al., 2017). Therefore, the characterization of MSW in Lahore can be used as a good reference to represent the situation for the management of MSW in most major cities in Pakistan.

In developing countries, solid waste management systems suffer from many problems, such as irregular collection service with low coverage, open dumping, improper burning to induce extreme air pollution, loose sorting systems, unpleasant odors, and pest control issues. As such, poor regulation or management of MSW can lead to serious health hazards in the surrounding environment (Ogawa, 1996). Studies have reported that uncontrolled landfills are the world's third biggest source of methane emissions, causing serious environmental degradation. According to the Pakistan Environment Protection Agency (Pak-EPA), Pakistan is ranked 135th for global methane emissions on a per-capita basis, contributing ~0.8% of the total global GHG budget (Zuberi and Ali, 2015). Moreover, uncontrolled MSW can also increase the breeding of dengue mosquitoes (Khalid and Ghaffar, 2015). Indeed, more than 40,000 cases of dengue virus infections were reported in Pakistan in 2010; among them, 17,256 cases (with 279 deaths) were registered in Lahore (Khan and Abbas, 2014). According to a recent report made by health officials in Farmer (2019), dengue virus has infected more than 10,000 people to lead to 20 deaths. The number of cases are increasing rapidly in Lahore and Rawalpindi (Farmer, 2019).

The handling of MSW is a steady and important challenge all across the world. In Pakistan, the Lahore Waste Management Company collects an average of 6500 tons of MSW every day with a collection efficiency more than 90%. Many of the problems with MSW treatment (such as improper segregation, poor collection, and transportation frequency) are primarily the result of insufficient collection equipment in Lahore. Although some fractions of MSW are recycled and reused, the proportion is not well defined due to poor recycling systems. Only 27% (on a weight basis) of the total waste is recycled by unofficial means, due to the lack of any recycling regulation in the country (Masood et al., 2014). Many recyclables (e.g., paper, plastics, and metals) are manually collected and sold by waste pickers (needy people) to unrecognized junk shop owners at various stages of MSW (e.g., from generation to final disposal).

The Lahore Waste Management Company produces ~500 and ~700 tons/day of compost and refuse-derived fuel (RDF), respectively, from collected MSW in Lahore. The RDF is mechanically separated and processed combustible fraction of MSW (Nasrullah et al., 2014). The higher energy content and more predictable properties of RDF (e.g., relative to MSW) make it superior fuel. In developed countries, the incineration of RDF has been in practice as a possible means to solve the waste and energy issues simultaneously (Rada and Andreottola, 2012)

Most of the collected MSW is placed in a landfill at the first scientific disposal facility in Pakistan, namely Lakhodair landfill, which occupies 43 ha of land. As this landfill facility does not have enough capacity and complete sanitary engineering, it cannot deal with all of the MSW generated from Lahore. Therefore, semi-equipped landfills and open dumping are mostly used. The MSW landfills are subjected to an array of biological, chemical, and physical processes that lead to gaseous and liquid emissions (Reinhart, 1993).

In addition, the leachate released from landfills is seriously contaminating ground and surface water, depending on the leachate composition and age of the waste landfills, because the semi-landfill facility in Lahore does not have any leachate treatment system. Indeed, there have been many efforts to renovate conventional dumpsites for MSW into better ones with sanitary landfill systems. However, it would be very difficult to acquire sufficient space and facilities. Except for composting and RDF, energy revitalization is an emerging option through combustion, gasification, and pyrolysis. The certain processes, including incineration, might be a salient strategy and can also obtain volume reduction of MSW, have a lower space requirement, and more efficient energy recovery than conventional landfill disposal (Eriksson et al., 2007; Huai et al., 2008).

Energy availability is considered as the lifeline for the country's economy in order to sustain commercial, industrial, and domestic activities. Non-renewable sources have remained the priority for energy production. According to an economic survey of the Government of Pakistan in 2015, the energy mix in Pakistan primarily depends on extraction of energy from non-renewable sources, as shown in Table 1. In 1980, the cheapest and environmentally friendly hydropower share of 70% was the major contributor to fulfill the energy demands of Pakistan. However, due to political instability and financial constraints, all of the elected governments preferred short-term electricity projects, which reduced the hydropower share down to 30%.

To meet energy demand, the share of hydropower was replaced with oil operated thermal plants. In 2008–2009, the Government of Pakistan paid 9 billion US dollars to import oil to overcome low efficiency thermal plants. This caused a great burden on the country's economy, followed by environmental pollution (Rehman et al., 2013). Low water levels in dams, a shortage of natural gas, and reliance on high cost fossil

Table 1
Energy mix of Pakistan in 2015.

Order	Source	MW	Percentage share
1	Gas	7494	30.18
2	Oil	9295	37.40
3	Coal	25.00	0.001
4	Hydro	7116	28.67
5	Wind	106	0.430
6	Nuclear	787	3.170
7	Total	24,823	100

fuels for energy generation are the main reasons for the serious energy crisis in Pakistan. Moreover, the energy gap between supply and demand expanded at an alarming rate. The economy's expected long run growth potential of 6.5% also decreased down to 2% due to an energy crisis in the country. At present, Pakistan has adopted the coal fired power plant technique to minimize the energy crisis under China-Pakistan Economic Corridor (CPEC) projects, adding a greater share to the non-renewable energy mix. These massive coal fired power projects aim to add electricity (7000 MW) to the national grid station by using imported coal until 2021. Recently, two plants have started operation to add 660×2 MW of electricity with the goal of contributing to the minimization of the energy gap. Unfortunately, a waste to energy program is still not a part of the energy mix of Pakistan. The aim of this study was also to assess the characteristics of MSW generated from Lahore, Pakistan, and to suggest potential sustainable options to minimize adverse the environmental impacts from the landfill of MSW.

2.2. Materials and methods

The social and economic structure was taken into consideration with the characterization study of MSW in Lahore, Pakistan. Different economic levels (*i.e.*, low USD (30–130), intermediate USD (320–640), and high income above USD 640) were also considered with commercial and institute zones, as shown in Fig. 1 and Table 2. The "U.S. Standard ASTM D5231" and "European Commission Methodology for the Analysis of Solid Waste" were used as the basis for this study. According to spot sampling method, a total of 12 homogenized samples of MSW were collected from 12 MSW carrying trucks (capacity 6000 kg/truck) from the Lahore Waste Management Company. It is assumed that one truck of MSW collection may represent wastes from 200 houses in one town. The shovel technique was used instead of the quartering method due to the size of the samples. Physical characterization of MSW was carried out with a sample of 0.5 m^3 from homogenized MSW from each truck by using a scale container. The combustibles and non-combustibles components of wastes were classified into 14 categories, as shown in Table 3. The defined combustibles fraction (e.g., biodegradable, nylon plastic bags, textile, diaper, and paper) of MSW comprises almost 81% of the total MSW composition as presented in Table 3. The overall sampling procedure remedy is presented in Fig. 2. Segregation and weighing of components were performed according to the classification guide for the physical composition of MSW (ASTM, 2003).

To track variations in physical composition of MSW around the years, the aforementioned physical characterization procedure was repeated quarterly and their average results for different socioeconomic levels are illustrated in Fig. 3. For a better understanding of the variation in MSW composition with reference to incineration process, the defined combustible fractions of MSW (including biodegradable, nylon,

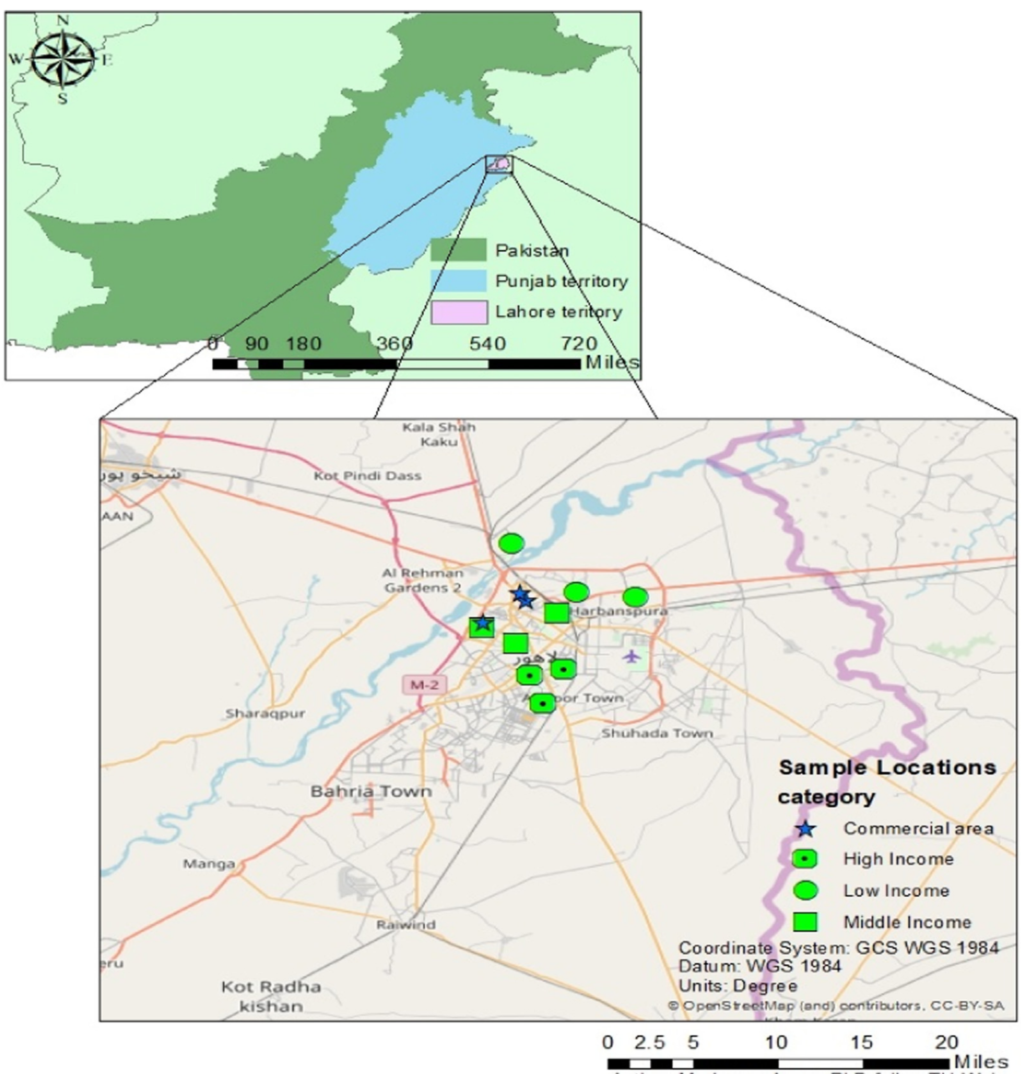

Fig. 1. Map of Pakistan and Lahore with the indication of sample locations.

Table 2
Sampling area classification for characterization of MSW in Lahore.

Order	Areas	Location 1	Location 2	Location 3
1	Low-income USD (30–130)	Salamatpura	Bogiwal	Shahdra
2	Middle-income USD (320–640)	Shakir Road	Gulshan-e-Ravi	Ghari Shahu
3	High-income above USD 640)	Hussain Chowk	Garden Town	Garden Town
4	Commercial/institute	Shah Alam Market	Moon Market	Saad Metha Hospital

Table 3
Component classification of Lahore MSW.

Order	Components	Explanation
1	Biodegradable	Food, fruits, vegetables, plants, etc.
2	Nylon	Plastic shopping bags
3	Plastics	All kind of plastics except PET
4	PET	Shampoo, detergent, and beverage bottles
5	Textile	All kinds of textile wastes
6	Paper-Cardboard	Newspapers, magazines, office paper, etc.
7	Tetrapack	Milk and juice cardboard
8	Metals	All kinds of metals
9	Hazardous	Accumulator, battery, medical waste, etc.
10	Elec-Electronic	Every type of electric and electronic wastes
11	Diaper	Baby diapers and sanitary pads
12	Non-combustible	Stone, demolition waste, bond, curbside
13	Glass	Every type of glass
14	Combustibles	Combustible waste that is undefined in other categories

textile, PET, and paper) were selected and subjected to individual proximate/ultimate analysis and heating value tests according to the respective ASTM standards (da Graça Madeira Martinho et al., 2008; Gidarakos et al., 2006). All the individual fractions of MSW were ground to a size less than 0.1 mm for the analysis. Moisture content of each fraction was determined by weighing samples into a pre weighted dish and drying at 105 °C in an oven to a constant weight. Then, the percentage loss in weight before and after drying was used to assess the moisture content. The volatile content was determined by heating the MSW fractions according to ASTM D 3175-11 under a control condition and measuring its weight loss. Ash content was found in accordance with ASTM D 3174-12. Proximate analysis was expressed as the mean from triplicate. The test for energy content and ultimate analysis were completed by using a bomb calorimeter (IKA C 2000, USA) and an elemental analyzer (2400 CHN, Perkin Elmer, USA), respectively, as presented in our previous work (Azam et al., 2019).

To quantify the total content of heavy metals, the selected dried samples were treated using aqua regia according to EN 13657 (2002). These samples were then analyzed by following the procedures of EN 11885 (2009) with the aid of a PerkinElmer Optima 8300 ICP-OES (inductively coupled plasma optical emission spectroscopy) spectrometer equipped with a SC-2 DX FAST sample preparation system. The concentration data were expressed as the mean from triplicate. A customized single element (Merck, Roth) standard was adopted for calibration. For preparation of leachate from the individual components of MSW, a liquid to solid ratio of 10 L/kg was used according to EN 12457-4 (2002). MSW components with a particle size below 10 mm were used to prepare the leachates in deionized water with tumbler agitation action for 24 h. After 10 min of agitation process, leaches were subjected to filtration process (0.45 µm) and subsequently analyzed by using the

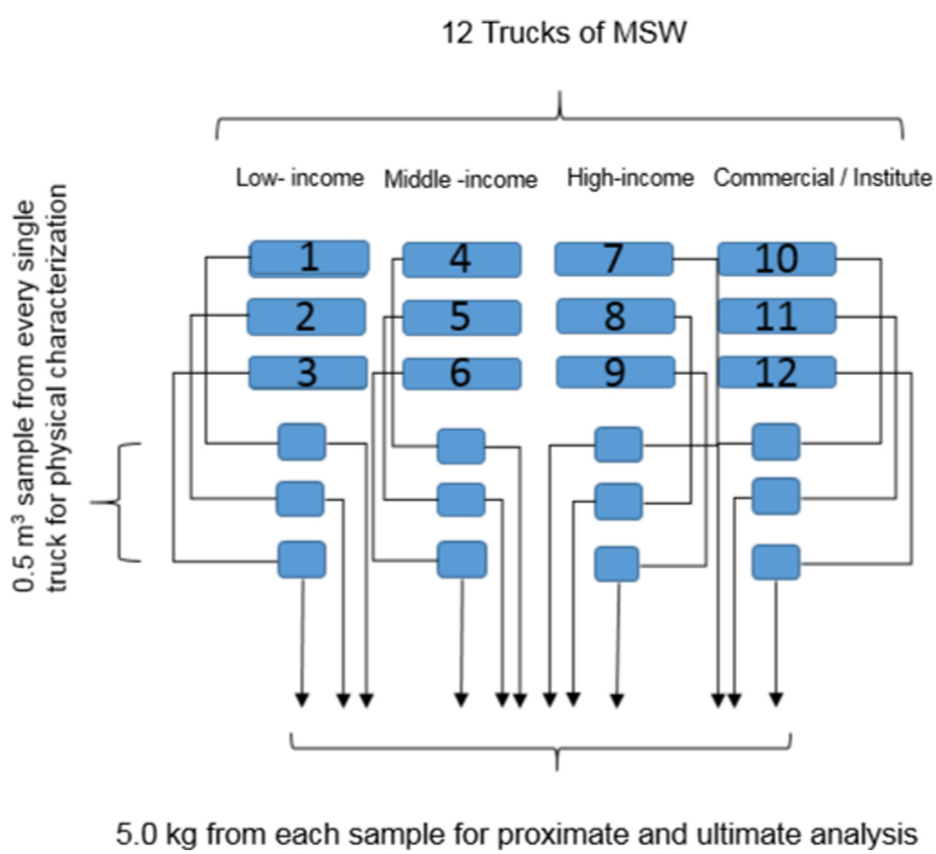

Fig. 2. The MSW sampling procedure used in this research.

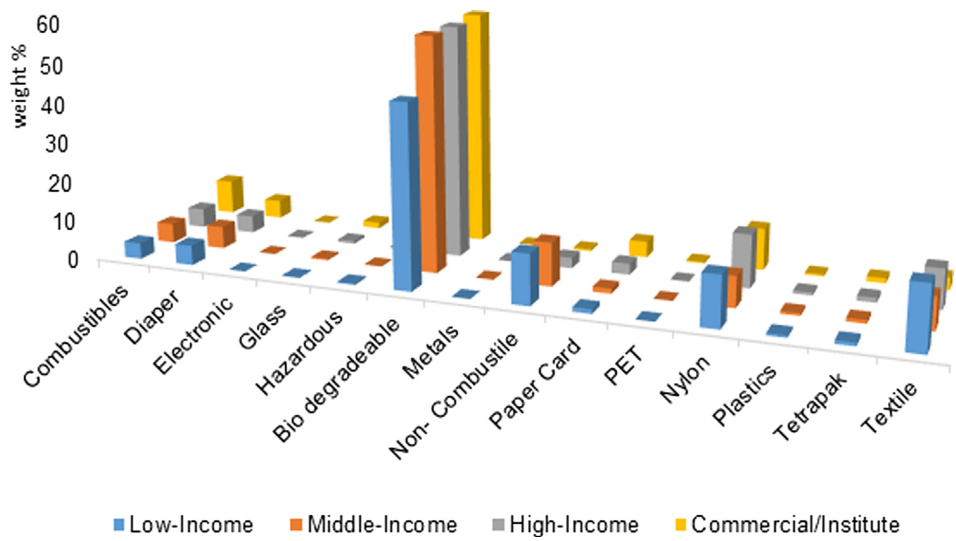

Fig. 3. Average composition (weight percentage basis) of MSW from different socio-levels of Lahore, Pakistan.

same ICP-OES as noted above. The purpose of these individual tests was to predict the change in chemical composition of combustible components of MSW that might occur due to variation in the physical composition of MSW.

3. Results and discussion

3.1. Physical characteristics

Different socioeconomic factors such as population density, life expectancy, income per capita education, and human development play a significant role in defining the quantity and quality of generated MSW. The heterogeneous nature of MSW and its physical composition were mostly dependent on socioeconomic levels (Figs. 3 and 4). The dominant waste category for all of the socioeconomic levels was biodegradable (56%), followed by nylon plastic bags (11%) and textile (9%). The high amount of biodegradables, especially food residue, would result in a high moisture content in the MSW.

The MSW in Lahore showed remarkable difference compared to that of developed countries, where systematic sorting of components (*i.e.,* paper, textile, and plastic) leads to valuable MSW composition (Kumar and Samadder, 2017). The results of low-income area (e.g., the lower percentage of biodegradable and the higher percentage of textile, nylon, and diapers) were noticeable. This variation was attributed to the high rate of population, consumption habits of the habitants, and to some extent religious fest and activities (*i.e.,* Eids, month of fasting). The highest percentage of nylon shopping bags (13%) for the high-income area was observed as an indicator of higher wealth levels. It should also be noted that the presence of high percentage of plastic bags and materials in all socioeconomic levels is a great environmental threat and concern. Due to inadequate waste collection system, its presence in undesirable places like sewers, storm drains, and roadsides can cause many undesirable consequences. The non-biodegradable plastic bags are not suitable for composting and combustion process as well. In commercial areas and facilities, the quantities of the undesired hazardous waste were the highest. The hospitals in the vicinity were the main sources of hazardous wastes as they were lacking incineration facilities to treat generated hazardous waste.

In all the socioeconomic levels, the low percentage of the paper fraction was noteworthy The paper fraction of MSW has been collected by unofficial means and utilized by two paper-pulp companies for the production of low quality pulp. Note that the energy production from MSW mainly depends upon high percentage of plastic and paper. The high level of paper fraction in MSW contribute to high heating value with low ignition temperature and low ash content in the energy recovery process. Therefore, low level of paper fraction in MSW may affect the efficiency of the energy recovery process (Yi et al., 2011).

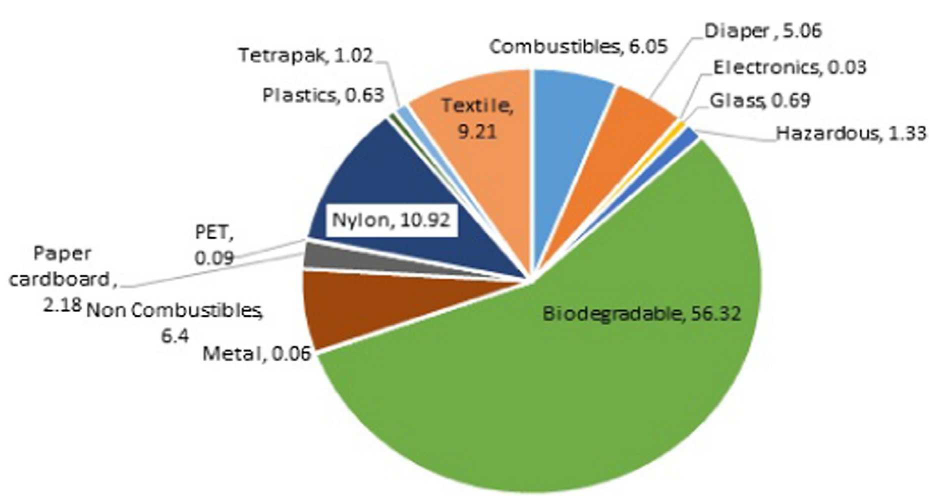

Fig. 4. Physical percentage composition of the MSW (Azam et al., 2019).

Table 4
The results of proximate and ultimate analysis of MSW components.

Order	Analysis (%)	Biodegradable	Textile	Nylon plastic bags	Paper	PET bottles
	Proximate analysis[ad]					
1	Total moisture	4	2.9	0.1	3.4	ND
2	Volatile matter	77.5	81.2	93.7	75.9	92.3
3	Fixed carbon [d]	8.5	10.8	0.7	1.9	7.5
4	Ash	9.6	5.0	5.5	18.8	0.2
	Ultimate analysis[daf]					
6	Carbon	62.5	58.4	78.7	50.5	62.0
7	Hydrogen	8.0	4.9	12.4	6.4	4.1
8	Nitrogen	0.4	0.6	0.12	0.22	0.05
9	Sulphur	0.1	0.16	0.02	0.55	0.01
10	Oxygen[d]	28.8	35.7	8.7	42.3	34
11	HHV[db] ($kJkg^{-1}$)	10,338	20,392	40,416	16,239	23,060

VM: volatile material, FC: fixed carbon, HHV: high heating value, ND: not detected.
d: calculated by difference, *ad*: air-dried basis; *daf:* dried ash-free basis.

3.1.1. Chemical characteristics

Proximate/ultimate analysis and heating values of MSW are of great importance for the evaluation of the energy recovery feasibility of a MSW management system (Rehman et al., 2013). The individual fractions of MSW on an air-dried basis are summarized in Table 4. To assess the overall chemical characterization and heating values of MSW by different socioeconomic levels, each fraction was summed based on a weight percentage of each component in the main stream of MSW, as shown in Table 5. One of the important parameters that affect the yield of incineration is the moisture content of MSW. Like other Asian countries, a high moisture content (40–50% measured at locations on as received basis, as compared to 20–30% in developed countries (Kumar and Samadder, 2017) in the MSW of Lahore was noticeable. The main reason for high and different moisture contents in various social economic levels in Lahore may have been (Kathiravale, 2003) due to differences in kitchen waste content and the inadequate sorting/collecting system for MSW. The high moisture contents of MSW leads to several concerns, including complexity associated with the recovery of recyclable items, an increased amount of leachate, and reduction in the net calorific value of the waste when incinerated (Zhang et al., 2010b).

One of the significant factors in the determination of energy content of MSW is the calorific value. Generally, researchers have reported the calorific value in relation to low heating value (LHV) and high heating value (HHV). LHV is the calorific valu, which does not consider the latent heat of vaporization during the complete combustion of waste stream. In contrast, HHV is the theoretical calorific value in which latent heat of vaporization is taken into account and is usually measured in bomb calorimeter (and sometimes calculated by equation). LHV has practical application in energy estimation and utilization in electricity generation from MSW incinerators (Komilis et al., 2014). The variation in HHV among different socio economic levels was noticeable. If MSW has a high content of moisture and ash, then its high heating values will decrease. The operation of the incinerator can then be affected by variation in the heating value (Baawain et al., 2017). The empirical models available for predicting the energy content (LHV) of MSW were employed for comparison, as shown in Table 6. The LHV 14,408 ($kJ\ kg^{-1}$) of MSW is calculated on the basis of HHV (using bomb calorimeter). This LHV shows a good agreement with the LHV values predicted from different empirical models. The LHV variations within different empirical models should be subject to different assumptions and limitations such as selected basis, units and particle size for analysis. (Kathiravale, 2003). Prediction of a LHV from the empirical model was a linear function of fixed carbon and volatile matter. However, the HHV was only dependent on volatile matter as the fixed carbon did not play a significant role in the calorific value of MSW (Kathiravale et al., 2003)

High values for volatile matter content in Lahore MSW will cause easier ignition and removal of a significant fraction of MSW in an incinerator. In the ultimate analysis, the results showed that carbon and oxygen were the most dominate components in the MSW samples. The high oxygen content will lead to higher reactivity during the incineration process. The carbon content in MSW was dependent on the proportion of biodegradables. The more biodegradables in MSW indicated less carbon content in comparison to non-biodegradables, which contributed more to the carbon content. In terms of environmental risk, the content of sulphur in MSW is quite low compared to coal. This may facilitate the process of co-combustion of coal and municipal waste to help reduce SO_2 emission during combustion process.

These physical and chemical characteristics of Lahore waste were quite similar to those of China and Malaysia (Kathiravale et al., 2003; Zhou et al., 2014). Inconsistency in the terms, units, and the basis used

Table 5
Results of proximate[ad] and ultimate analysis[daf] of Lahore MSW.

Order	Analysis (%)	Area classification				
		Low	Middle	High	Commercial/ Institute	Average
1	Total moisture	3.1	3.5	3.2	3.4	3.3
2	Volatile matter	80.3	79.3	80.1	79.2	79.7
3	Fixed carbon	7.4	7.70	7.1	6.9	7.2
4	Ash	8.3	9.2	9.1	9.7	9.1
5	HHV ($kJkg^{-1}$)	17,533	14,588	16,413	15,100	15,978
6	Carbon	63.5	63.2	63.8	63.3	63.6
7	Hydrogen	7.9	8.0	8.2	8.3	8.19
8	Nitrogen	0.4	0.42	0.3	0.3	0.4
9	Sulphur	0.1	0.1	0.11	0.1	0.1
10	Oxygen	27	27.8	27.0	27.1	27.0

Table 6
Empirical models used for prediction of the energy content of MSW.

Order	Model based on physical composition	Energy content ($kJkg^{-1}$)
1	Conventional H_n = 88.2R + 40.5 (G + P)-6W	13,647
2	Model based on proximate analysis traditional model H_n = 45VM-6 W	13,417
3	Bento's model H_n = 44.75VM-5.85 W + 21.2	13,752
4	Model based on ultimate analysis H_n = 81C + 342.5(H-O/8) + 22.5S-6(W + 9H)	14,713

Hn: net calorific value in $kJkg^{-1}$, R: weight % of plastic, VM: % volatile matter, G: weight % garbage, P: weight % paper, W: water percent (air-dried basis) for the different components of the proximate and ultimate analysis as well as the heating values caused problems when comparing values with the literature values. It is evident that incineration of MSW with these analysis values might face several problems, such as difficulty in ignition, unsteady flame, and incomplete combustion of MSW, compared to the reported values from China and Malaysia. To incinerate MSW with high moisture and low energy contents, supplementary fuel would also be required with additional operating costs (Cheng et al., 2009; Cheng et al., 2007). Furthermore, MSW should be transported to a waste pit for six to seven days before it is fed into the incinerator in order to improve economic and combustion stability of the incinerator (Zhang et al., 2010a).

The conventional incineration plants used in developed countries might not be a good choice for Asian countries based on the results of a high portion of biodegradables containing high moisture and low calorific values (Kumar and Samadder, 2017) Therefore, the application of advanced incinerators like a fluidized bed type would be a better option to overcome these issues. For instance, China has utilized fluidized bed incinerators to counter the problems of high moisture and low energy content: currently 28 of such plants are in operation to generate electricity by processing MSW (800 tons /day) (Zhao et al., 2016). Inadequate sorting systems for various MSW fractions at the place of generation is of high concern as well; improvements in sorting system can greatly enhance MSW suitability for various incineration processes.

3.1.2. Heavy metal content

The generated MSW is exposed to different weather conditions and natural processes during storage, utilization, or disposal. Certain heavy metals (e.g., chromium, arsenic, lead, cobalt, nickel, zinc, cadmium, barium, boron, and manganese) are frequently detected in MSW (Quaghebeur et al., 2013). Among these metals, chromium, cadmium, and arsenic are potentially carcinogenic. In contrast, other metals, such as nickel, lead, and mercury, contain a well spread range of toxic effects, including teratogenicity (Christensen, 1995; Domingo, 1994). These heavy metals may result in contamination of different water sources, especially ground and surface water due to the leaching process. Therefore, the monitoring of heavy metals in MSW is necessary to evaluate the contamination potential.

The concentrations of the toxic metals detected in the selected combustibles fraction of MSW are summarized in Table 7. Among them, zinc, chromium, manganese, and barium were present in high concentrations amongst all of the metals examined. The components of MSW such as textile, paper and nylon plastic bags are the major contributors to the high concentrations of manganese, nickel, zinc, and chromium. Arsenic comes primarily from nylon plastic bags, textile and PET bottles. However, it is worth noting that lead and cadmium mostly stem from paper component of MSW. Their concentration levels were in most cases comparable to those commonly reported in the literature (Kumar et al., 2016; Rong et al., 2017). However, the concentrations of lead and cadmium were considerably lower and that might have been due to the absence of wastes like lead-cadmium batteries, paint and pigments (Majolagbe et al., 2017).

The results of the leaching test for the samples are presented in Table 8. These values have been compared with the toxicity limits value for the solid waste set by the European legislation. The result indicates that no serious leaching of heavy metals took place during leaching test of selected components of MSW. It is worth noting that leaching content of metals like Cd, Cu, Zn, Sb, Mo, Sn, Co, and in all samples is below the limit values for inert waste category (Table 8). Only content of certain metals like Hg, Ni and Pb is at verge of inert to non-hazardous limits. The leaching capacity of heavy metals is very much pH-dependent. The standard test EN 12457-4 used for leaching of samples does not contain acidic conditions, whereas the acidic conditions of other leaching tests, such as HJ/T300, make the environment favorable for the leaching process.

3.2. Economic aspect of energy recovery

Thermal power plants in Pakistan generate electric power of 8000 MW mainly using diesel and furnace oil. The diesel and furnace oil have to be imported, which consumes foreign reserves. On the other hand, based on the population of Lahore (about 11 million) and the average generation rate of MSW (0.65 kg/capita/day), the amount of MSW generated on a daily basis is simply calculated as 7150 tons/day. As stated earlier, incineration of MSW leads to several benefits, such as reduction in the mass (~70%) and volume (~90%), efficient energy recovery, and complete disinfection of pathogenic waste (Li et al., 2003; Sakai et al., 1996). Installation of incineration facilities will not only decrease the dependency on fossil fuels to meet energy demands, but can also be an excellent alternative for MSW management.

The estimated energy recovery potential of MSW and RDF incineration is shown in Table 9. The energy potential was calculated for capacity of 2000 tons/day of MSW and RDF. It is expected that there might be an increase in demand of RDF for use in cement and coal sector. Note that the use of RDF in industrial application should offer more flexibility than incineration process with better ecological advantages (Çepelioğullar et al., 2016). Therefore, keeping an eye on increase in demand of RDF, the capacity of 2000 tons/day was selected for this facility which is easily available amount of combustible fraction of wastes for incineration process. The average calorific values of MSW (8356 kJ kg^{-1}) and RDF (27,000 kJ kg^{-1}) were utilized to acquire overall spectrum about energy potential. The energy potential of RDF has almost doubled the energy potential of MSW.

The estimated amount of methane emission from landfills in Pakistan is 14.18 Gg per year. This release of methane to atmosphere traps the heat with a 22-fold greater greenhouse effect than CO_2 (Zuberi and Ali, 2015). Thus, it is of vital importance to adopt good strategy to address the issue of methane emission from landfills. As stated earlier, landfills in Pakistan are not designed to trap methane for its utilization as fuel. Therefore, the incineration of MSW will be a good alternative technique for reduction in GHG emission compared to landfilling of

Table 7
The results of heavy metal analyses (mg/kg: dry weight basis).

Element	Biodegradable	Textile	Nylon bags	Paper	PET bottles	MSW
As	< 0.41	2.4 ± 0.1	3.6 ± 0.4	0.48 ± 0.1	2.1 ± 0.2	< 0.72
Ba	15.1 ± 0.08	20.1 ± 0.8	32.9 ± 7.0	32.4 ± 0.1	4.04 ± 0.1	94.2 ± 0.1
Cd	< 0.2	0.71 ± 0.1	0.95 ± 0.4	0.87 ± 0.1	< 0.38	1.1 ± 0.1
Co	1.5 ± 0.1	3.44 ± 0.1	12.9 ± 0.3	2.23 ± 0.4	< 1.93	< 2.09
Cr	5.2 ± 0.0	40.6 ± 0.2	28.1 ± 0.3	28.2 ± 0.1	21.8 ± 0.3	59.1 ± 0.2
Hg	0.01	0.04	0.20 ± 0.01	0.06	0.04 ± 0.01	0.03
Mn	16.1 ± 0.0	53.5 ± 0.9	31.7 ± 0.3	74.8 ± 0.4	15.9 ± 0.1	54.5 ± 0.1
Ni	1.02 ± 0.1	12.3 ± 0.3	16.8 ± 0.50	16.1 ± 0.1	9.9 ± 0.4	27.4 ± 0.5
Pb	< 0.58	< 0.911	< 0.92	7.6 ± 0.4	< 0.904	< 0.9
Zn	19.2 ± 0.1	160 ± 1.0	85.3 ± 0.9	52.5 ± 0.1	14.8 ± 0.1	87.6 ± 0.4

Table 8
Leachability of heavy metals (mg/kg) from samples using EN 12457-4 (2002).

Element	Biodegradable	Textile	Nylon bags	Paper	PET bottles	TL1	TL2	TL3
As	0.06 ± 0.04	< 0.03	< 0.03	< 0.03	< 0.03	0	2	–
Ba	0.40 ± 0.01	< 0.03	0.1	0.13	< 0.03	–	–	–
Cd	0.02 ± 0.0	< 0.01	< 0.01	< 0.01	< 0.01	0.04	1	5
Co	< 0.09	< 0.09	< 0.09	< 0.09	< 0.09	–	5	–
Cr	< 0.06	< 0.06	< 0.06	< 0.06	< 0.06	0.5	10(20)	70
Hg	0.01 ± 0.0	0.01	0.01	0.01	0.01	0.01	0.1	2
Mn	0.77 ± 0.01	0.1	< 0.04	0.7	< 0.04	–	–	–
Ni	< 0.03	< 0.03	< 0.03	< 0.03	< 0.03	0.4	10	40
Pb	< 0.36	< 0.36	< 0.36	< 0.36	< 0.36	0.5	10(30)	50
Zn	1.3 ± 0.01	4.09	3.06	2.2	< 0.03	4	50(100)	200
pH	4.3	7.73	7.72	7.6	6.9			
Conductivity (mS/cm)	3.6	0.48	0.2	1.5	0.1			

TL1; toxicity limits inert waste, TL2; toxicity limit non-hazardous waste, TL3; toxicity limit hazardous waste.

Table 9
Energy recovery potential from MSW (2,000 ton/day) by incineration.

Order	Sample	Conversion efficiency (%)	LHV ^{ar} (kJkg^{-1})	Energy recoverable per ton of fuel (kWhrton^{-1})	Total energy recovered from (2000 ton/day) (MW)
1	MSW	25	8356	581	48
2	RDF	25	27,000	1117	93

ar; as received basis.

MSW. This will reduce the share of fossil fuel and greenhouse gases. The addition of incineration technology will thus be a positive move towards the promotion of renewable energy sources in the country.

As in Europe, a major portion of the generated steam from the incineration of MSW is being used for central district heating in addition to the production of electric power. In the case of Lahore, the installation of an incineration facility near the industrial zone (*i.e.*, Sunder state) will be more effective and beneficial regarding MSW transportation and economical utilization of steam. Moreover, the steam from an incineration facility will have economical value by selling it to different industries in the Sunder state or it may be utilized in steam turbine chillers for central cooling during the long summer season. The vitalization/utilization of MSW incineration in Lahore would lead to mitigation of disposal and the environmental problems of MSW as well as reduction of GHG emissions.

4. Conclusions

Understanding of the physical and chemical composition of MSW is of great importance regarding future planning and management of MSW. The establishment of the “Waste to Energy” program would be beneficial to Lahore based on the results of proximate/ultimate analysis and the heating values of MSW. Indeed, the incineration of 2000 tons MSW/day has an energy recovery potential of 48 MW as well as a high return with environmental benefits, including a reduction in GHG emissions. However, high moisture content, inadequate collecting systems, and low collection efficiency of municipal departments are still challenges.

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The authors have no potential conflicts of interest to declare with respect to the research, authorship, and/or publication of this article.

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