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Co-firing Municipal Solid Waste with Coal - A Case Study of Warangal City, India

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ABSTRACT

Municipal solid waste management has become an important challenge in the developing countries. Treatment using thermal methods, especially by incineration is advantageous in comparison with biological and chemical treatments, as they require less time and space for the reduction of huge quantities of wastes and also generates energy. As the composition of municipal solid waste (MSW) and its calorific value is inconsistent for power generation, we have studied the possibility of blending MSW with an auxiliary fuel such as coal. The study was conducted in the Warangal city (in Telangana State of India) which produces around 220 tonnes of MSW per day. Various blending proportions of MSW and coal were analysed and quantified the calorific value, gaseous emissions (NOx, SO_2 and CO_2) and also estimated the cost of production. We found that, blend of MSW and coal in the proportion of 90-80% and 10-20% respectively, is optimal in terms of waste processing and lower gaseous emissions. The cost-benefit analysis for the two scenarios consisting of either inclusion or exclusion of food wastes in the MSW validates the viability of co-firing as a better waste management practice with a minimum assured gain of Rs. 0.3 million per day.

INTRODUCTION

Solid waste management has become a daunting task for urban municipalities in India. The production of municipal solid waste (MSW) has increased tremendously with the improvement in lifestyle and growing consumerism. It is reported that India produces around 1,43,000 to 1,70,000 metric tonnes of MSW per day (Mani and Singh 2016). Nearly 40 % of the urban MSW is produced from metro cities of India (Annepu 2012). According to the Central Pollution Control Board (CPCB) report, the urban municipal authorities in India are unable to upgrade or scale up their solid waste management facilities (CPCB 2016) with the rise in population. The gap between growing urban population and waste treatment facilities is becoming wider. Further, it is reported that urban population in India is projected to reach 439 million by the year 2022 with a share of 32.5% of the country's population (MoSPI 2017), and by year 2030 the share would rise to 40.8% (UNPF 2007). Hence, scientific management of MSW takes center stage in order to make Indian cities sustainable and eco-friendly.

The MSW in urban areas is collected, transported and processed, then the remaining waste is sent to open dump sites (Singh et al. 2011). The major processes involved in the treatment of MSW are sanitary landfill disposal, incineration and composting (Atalia et al. 2015). The existing infrastructure for MSW treatment (Table 1) is insufficient for the humongous amount of waste that India generates. Nearly 90% of the MSW in India ends up in open landfills (Kumar et al. 2017) as it involves less cost implications and the practice is prevalent in many Indian cities (Sharholy et al. 2008). Dumping causes severe problems like leachate contamination with groundwater, bad odour and fugitive emission around the dump sites (Shashidhar & Ajit Kumar 2011). In order to avoid environmental damage, the MSW is to be managed scientifically. If the current practice of open dumping of MSW is continued, the area required for the disposal of waste generated in the year 2047 (~230 million tonnes per year) would be around 1400 km^2 (Annepu 2012), which is equivalent to cumulative areas of three mega cities of India - Mumbai, Chennai and Hyderabad.

Waste-to-energy is becoming a best management choice for treating wastes now-a-days, as it is a two-pronged approach to address the waste volume reduction and energy generation (CPCB 2016, Yap & Nixon 2015). Especially through incineration, 70% of weight and 90% of volume of MSW can be reduced (Tian et al. 2012). Nearly 130 million tonnes of MSW is fired in over 600 waste-to-energy facilities worldwide (Xu et al. 2016). Also, producing energy from the discarded MSW is a potential energy source to lessen the dependence on fossil fuels (Kaplan et al. 2009). The energy from waste can be produced by two methods, either by direct combustion (e.g., thermo-chemical meth-

Table 1: Status of MSW processing facilities in India as of year 2015-16. Source (CPCB 2016).

Municipal solid waste processing facilities	Composting	Vermi-composting	Biogas	RDF (refuse derived fuel)	Sanitary landfills	Dump sites
Number of plants setup	209	208	82	45	-	-
Number of plants operational	168	141	67	26	175	1247

ods like incineration, pyrolysis and gasification) or by the production of combustible fuels-methane and hydrogen (e.g., biochemical methods like anaerobic digestion, biological treatments) as mentioned by Cheng & Hu (2010). Thermo-chemical methods are best suited for high calorific wastes and the time required for processing is very short. Whereas, biochemical methods are suitable for biodegradable wastes which are organic in nature, however, the time consumed is very high as compared with thermo-chemical processes. According to the Ministry of New and Renewable Energy of Indian Government, India has a potential of 1500 MW of energy from MSW, whereas only 2% is realized so far (EIA 2013). As of year 2015-16, India has 26 operational RDF (refuse derived fuel) plants (out of 45 plants installed) which are producing around 156 MW of energy (CPCB 2016).

In general, the waste-to-energy plants in India have not sustained in operation owing to multiple reasons such as, low calorific value of waste and high moisture content (Talyan et al. 2008), lack of logistic and financial planning (Kalyani & Pandey 2014), lack of expertise (Srivastava et al. 2005), and poor waste segregation (Chattopadhyay et al. 2009). Supplementary fuels like coal, cotton waste and sawdust etc. are usually added to MSW in order to improve the consistency and to make it suitable for the combustion. Furthermore, with the addition of coal as an auxiliary fuel to MSW, studies suggest that the emissions resulting from incomplete combustion of MSW can be reduced substantially (Bhuiyan et al. 2018, Narayanan & Natarajan 2007, Surroop & Juggurnath 2011). Peng et al. (2016) reported a reduction in PAHs (polycyclic aromatic hydrocarbons) emissions with co-firing MSW and coal, and Suksankraisorn et al. (2004) have studied the NO_x, SO_X and CO emissions and reported a significant reduction in CO. Co-firing biomass (including agriculture waste, forest products and MSW etc.) with coal is being encouraged worldwide as a policy decision to deliberately reduce the dependence on fossil fuels and to reduce the green house gas emissions (IRENA 2013). India is well placed in terms of biomass supplies both from MSW and agricultural wastes, which has to be utilized for solving both the waste management issues and energy deficiency (Rathnam 2013).

We have studied the MSW characteristics of Warangal city in Telangana State of India, as the city is uniquely positioned in the country where efficient door-to-door MSW collection system is in place (CPHEEO 2014). However, at present the MSW is not been processed in a scientific manner, due to which it has become difficult to recycle and transform the solid waste. As a result, huge quantity of solid waste is getting accumulated at dumping sites at Madikonda, Shahimpet and Ramapura on the outskirts of the city (ISWM 2016, Warangal City Development Plan (CDP) 2011). Moreover, transportation of the garbage collected across the city limits to the dumping yards has become a cost intensive task. In this paper, we discuss various aspects of co-firing MSW with coal in Warangal city with broad objectives to: (1) verify the suitability of co-firing MSW with coal in incineration process for power generation, (2) derive optimum blend proportions of coal and MSW in terms of economic viability and reduction in gaseous emissions, and (3) perform the economic analysis to get viable working model of waste management.

MATERIALS AND METHODS

Study area: Warangal is the second largest city in the State of Telangana (located 17.9° N, 79.6° E) sprawling in an area of 110 km^2 (Warangal City Development Plan (CDP) 2011) and having 0.81 million population according to 2011 census (ISWM 2016). The city's weather is almost dry with temperature ranging from 20-48°C and the rainy season which lasts from June to September with 550 mm of average precipitation. As per 2011 census of India, Warangal is one of the cities which has seen rapid urbanization from 19% to 28%. The city generates municipal solid waste of 0.251 kg per day per capita, whereas country's average generation is 0.11 kg (CPHEEO 2014). On an average, around 200 to 300 metric tonnes of waste is produced in the city every day (Shashidhar & Ajit Kumar 2011) out of which, households, commercial establishments, street sweeping and drains contribute in 72%, 13.5%, 5.5% and 9% respectively (ISWM 2016).

Sample collection and analyses: The MSW samples were collected from Kasibugga ward of the city where a door-to-door collection system is followed and the ward is assumed to represent the social and economic strata of the city. The ward has 2,408 households with a population of 10,382

Table 2: Elemental composition of different categories of MSW and coal.

Sl. No.	Sample	C%	H%	N%	S%	O%	Ash%
1	Paper and cardboard waste	42.4	5.6	1.5	0.15	45.65	4.7
2	Plastic waste	76.4	7.5	1.2	0.2	9.5	5.2
3	Food waste	45.56	6.4	7.66	0.08	34.3	6
4	Garden waste	50.7	6.51	3.4	0.18	33.51	5.7
5	Coal	50.8	3.54	1.43	0.50	11.13	32.6

Table 3: Elemental composition of various blends of MSW and coal.

Blending proportions of MSW and Coal	Coal with MSW (including food waste)					Coal with MSW (excluding food waste)				
	C%	H%	N%	S%	O%	C%	H%	N%	S%	O%
Case-1 100% MSW + 0% Coal	49.13	6.41	5.25	0.12	37.80	54.07	6.56	2.79	0.17	30.88
Case-2 90% MSW + 10% Coal	49.23	6.23	5.01	0.14	36.17	53.77	6.29	2.67	0.20	29.09
Case-3 80% MSW + 20% Coal	49.34	6.04	4.76	0.17	34.40	53.46	6.01	2.54	0.23	27.26
Case-4 70% MSW + 30% Coal	49.47	5.83	4.48	0.20	32.46	53.15	5.72	2.41	0.26	25.39
Case-5 60% MSW + 40% Coal	49.60	5.60	4.17	0.23	30.34	52.83	5.42	2.28	0.29	23.50
Case-6 50% MSW + 50% Coal	49.75	5.34	3.83	0.26	27.99	52.51	5.12	2.15	0.33	21.57
Case-7 0% MSW + 100% Coal	50.80	3.54	1.43	0.50	11.13	50.8	3.54	1.43	0.50	11.13

persons (DCO 2011). The unsorted MSW generated from each house is collected by the municipality in a mechanical trolley and all the waste from the ward is sent to the Dry Resource Center (DRC). At DRC the waste is sorted into two categories-dry waste and wet waste. Dry waste comprises paper, cardboards, plastics, glass and metals, while wet waste comprises the organic waste-kitchen and garden waste. Representative waste samples were drawn from multiple locations of unsorted MSW pile at DRC and the samples were mixed thoroughly. In order to reduce the sample volume and to get the uniformity, cone and quarter method was followed (Choi et al. 2008). The reduced sample weighing 10 kgs was then sorted into five categories viz. food waste, paper & cardboard waste, plastic waste, garden waste and miscellaneous wastes (metals and glass). The procedure was repeated once a fortnight and a total of four such samples were analysed and the percentage compositions were averaged. The sampling campaign was done during the winter of 2017 and any effects due to seasonal variations or weekly variations on the MSW composition and waste generation trends were not investigated in the study. And, the coal samples used for co-firing the MSW in the study were obtained from the SCCL (Singareni Collieries Company Limited) coal fields situated near Ramagundam city. The coal is graded as G-10 quality having a calorific value in a range of 4301 to 4600 kCal/kg (SCCL 2017), and it is used in nearby thermal power plants in the State.

The moisture content of the waste was measured by oven drying (105°C for a duration of 24 hours) a representative sample of 50 g taken from each waste category. The sorted wastes were shredded in order to achieve uniformity. Similarly, the ash content was determined using Muffle furnace by charring the sample at 550°C for a duration of 2 hours.

The remaining sorted samples were air dried and then powdered for elemental analysis. Two grams of the powdered sample from each waste category was fed into CHNS analyser. Total carbon, nitrogen, hydrogen and sulphur content of the samples were estimated as percentage of dry weight of the sample. Whereas, the percentage of oxygen was calculated by subtracting percentages of ash and measured elements from 100 (i.e. 100 - (C+H+N+S+Ash)). Stoichiometric mass balance of elements viz. carbon, sulphur and nitrogen was done to estimate the gaseous emissions from the combustion processes by assuming complete oxidization ($C+O_2 \rightarrow CO_2$, $S+O_2 \rightarrow SO_2$ and $N+O_2 \rightarrow NO_2$).

MSW energy potential: Calorific value of the samples was determined by bomb calorimeter, in which the oven dried samples of 1 g were burned in the steel bomb. The difference in initial and final temperatures of the coolant was used as a measure in determining the calorific value, according to the following equation.

$$Calorific value (Cal/g) = \frac{Standard factor of 1311 \times Rise in Temp.}{Mass of sample}$$

The potential of MSW in co-firing with coal was estimated based on the typical efficiency parameters of a thermal power plant (Suksankraisorn et al. 2004). The following set of equations were assumed for power calculations.

Available Power at Furnace, E = Mass of MSW (kg/day) × calorific value (kJ/kg)

Power available at boiler = E × 0.85 (kg/day)

Power available at turbine = E × 0.85 × 0.95 (kg/day)

Power produced at generator = $\frac{E \times 0.85 \times 0.95}{1000 \times 24 \times 60 \times 60}$ (Mega Watts)

Cost-benefit analysis: The cost-benefit analysis was done to estimate the benefits in production of energy from various blends of MSW and coal. We have calculated for two extreme cases- (a) case-1: using MSW alone as fuel, and (b) case-7: using coal alone as fuel. Based on the data obtained from the two cases, we have interpolated the cost-benefit data for intermediate blend proportion of coal and MSW. In intermediate cases from case-1 to 7 the MSW share was decreased, while that of coal was increased (case-2: 90% MSW + 10% coal, case-3: 80% MSW + 20% coal, case-4: 70% MSW+ 30% coal, case-5: 60% MSW + 40% coal and case-6: 50% MSW + 50% coal). The data for estimating the costs incurred in various operations of power generation such as transportation of fuel, operation and maintenance of plants and cost of fuel itself were obtained from already operational industries. MSW related data were obtained from waste-to-energy plant at Bawana, New Delhi (Jain et al. 2014) and data on coal based energy plants were obtained from National Thermal Power Corporation's (NTPC) power plant at Singrauli, Uttar Pradesh, India (Mittal et al. 2012). The selling price of unit of power (in kWh) was obtained from Telangana Southern Power Distribution Company Limited (TSPDCL). The capital costs were not included in this analysis in order to simplify the calculations.

Further, we have also studied elemental compositions, gaseous emissions, energy potential and cost calculations for MSW excluding the food wastes as different scenarios. The separate analysis for MSW including and excluding food waste aids informed decision on whether the benefits of separating food waste is significant in any way. The economic aspects of utilization of segregated food waste for biomethanation is also considered for cost-benefit analysis.

In order to objectively compare the best blend of MSW and coal, we have used an objective function considering three factors viz., reduction in MSW volume, emission of NO_2 and SO_2 by assuming equal weights, as shown below:

$$Score_i = \frac{MSW_i}{MSW_{max}} + \left(1 - \frac{NO_{2i}}{NO_{2max}}\right) + \left(1 - \frac{SO_{2i}}{SO_{2max}}\right)$$

MSW_i is the weight of waste consumed in the energy generation process, which is compared against the maximum possible consumption, MSW_{max}. $NO_{2,i}$ is the value of NO_2 emission for i^{th} case and $NO_{2,max}$ is the maximum emissions from all the cases considered. Similarly SO_2 values can be calculated. Ideally, the case with score 3 (maximum possible) will be the best one with maximum waste reduction and minimum gaseous emissions. The scores were calculated for each case of the two scenarios - MSW including and excluding food wastes.

RESULTS AND DISCUSSION

Physical characterization of MSW and coal: Food wastes contribute to 51% of the MSW, followed by garden wastes (34%), plastics (8%) and others (Fig. 1). The share of food wastes in MSW of Warangal city is higher than the national average of 41% (Sharholy et al. 2008). Moisture content is maximum in food wastes to the tune of 60% and minimum in plastics and paper wastes. Ash content is around 6% for garden and food wastes. The plastic waste has highest calorific value of 38 MJ/kg and the food waste has lowest value of 5.6 MJ/kg (Fig. 2). The coal samples used in the study has calorific value of 18.6 MJ/kg, moisture content of 5.2% and ash content of 32.6%.

Elemental composition of MSW and Coal: Analysis shows that elemental carbon is highest in plastic wastes (76.4%) followed by coal (50.8%) and garden wastes (50.7%). Hydrogen is also maximum in plastic wastes (7.5%) followed by garden wastes (6.51%) as given in Table 2. It is observed that, although, MSW has comparable or some times even better elemental composition than coal, owing to its heterogeneity, the MSW cannot be directly used for combustion. It needs to be blended with auxiliary fuel-coal for consistent generation of power.

The composition of elements present in various blends for two scenarios of MSW-including and excluding the food wastes are presented in Table 3. Carbon and hydrogen contents were found to be maximum in case-1 of MSW excluding of food waste, whereas there is a significant drop in

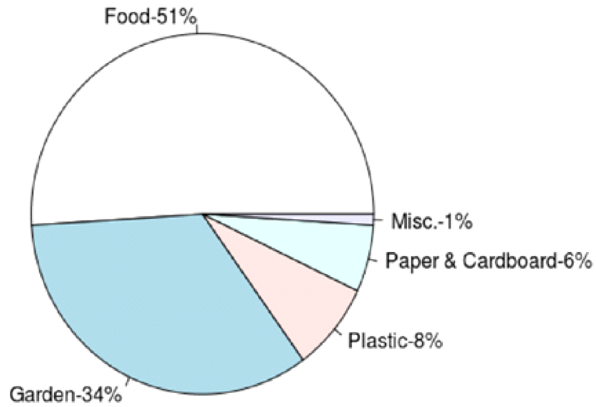

Fig. 1: Composition of municipal solid waste generated by residential area Kasibugga of Warangal city.

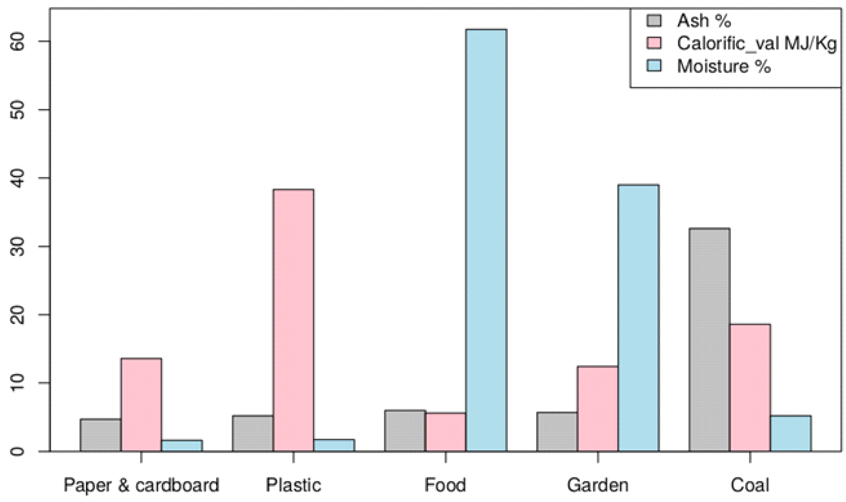

Fig. 2: Moisture, ash and calorific values of various categories of MSW and coal.

nitrogen content. The changes in elemental composition will have implications on energy potential and gaseous emissions.

Energy potential and MSW utilization: Energy potential is directly proportional to the calorific value and the rate of feed into the boiler. As Warangal city generates around 220 tonnes of MSW per day, it is assumed that the maximum available MSW for energy production is 220 tonnes/day and the same amount is considered for the rest of calculations. The maximum power possibly available at the furnace using all the MSW (case-1) would be 27.93 MW (220 times 10.97 MJ/kg). If the same amount of power is to be generated using coal alone (case-7) the quantity of coal required will be 129.81 tonnes/day. The amount of MSW and coal required for intermediate cases-2 to 6 are estimated according to the proportions of the blend (Table 4).

Further, if all the food waste from MSW is separated for being utilized in composting or bio-gasification, the MSW consisting only wastes from garden, plastics and cardboard will be fired for power generation. The maximum quantity of waste available in the scenario excluding the food waste is 105.6 tonnes/day (case-1) and maximum power possibly available at the furnace would be 20.7 MW (105.6 times 16.97 MJ/kg).

Emissions: For complete combustion, the amount of oxygen required for each blend combination is calculated based on stoichiometric equations. Nearly 25% of excess air is considered according to Mittal et al. (2012). The excess air required per day and emissions from combustion are tabulated in Table 5. The amount of excess air required for MSW excluding the food waste is more compared to MSW including food waste. The carbon, hydrogen and sulphur contents are more in MSW excluding food waste. Nitrogen and oxygen are less in MSW excluding food waste. This shows that more amount of air is required for combustion of MSW excluding food waste. Although, supplying the excess air will not be a major concern, however, it may effect the operational expenditure of the energy plant. The CO_2 and SO_2 emissions from the combustion of MSW is more than MSW excluding food waste, whereas the NO_x and ash content are less. The reasons for more CO_2 and SO_2 in MSW excluding food waste is due to high carbon and sulphur content in the composition (Table 3). Co-firing of coal and MSW generated lowest amounts of total PAHs than combustion of MSW and coal alone, whereas, combustion of MSW alone generated high quantities of PAHs in the range of 111.28 µg/g - 10,047.22 µg/g (Peng et al. 2016). Suksankraisorn et al. (2004) reported a significant reduction in CO concentration in co-firing MSW with coal.

Cost-benefit analysis: If MSW including the food waste alone is considered for generation of power, the maximum possible generated power is 22.5 MW (0.67 million units). Our estimates show that the cost incurred for the power generation from collection and transport of MSW (including food waste) and operation and maintenance activities will add to Rs. 1.5 million. Profit obtained by the power generation from the MSW is estimated by subtracting the cost incurred in power production from the selling price of the electricity (Rs. 2 million, @Rs 3.8 for one kWh (TSERC 2016)), which is Rs. 0.5 million/day (Table 6). Similarly, the cost incurred for the generation of power by using only MSW excluding of food waste is estimated as Rs. 1.34 million and the profit is estimated as Rs. 0.18 million/day.

Although, firing of MSW (with or without food wastes)

Table 4: MSW energy potential and utilization at different blending ratios.

Blending proportions of MSW and Coal	MSW including food waste						MSW excluding food waste					
	MC%	Ash%	CV MJ/Kg	MSW Tonnes	Coal Tonnes	Total (MSW + Coal) Tonnes	MC%	Ash%	CV MJ/kg	MSW Tonnes	Coal Tonnes	Total (MSW+ Coal) Tonnes
Case-1 100% MSW+0% Coal	44.98	5.70	10.97	220.00	0.00	220.00	28.17	5.495	16.97	105.6	0	105.6
Case-2 90% MSW+10% Coal	42.53	7.35	11.73	198.00	12.98	210.98	26.05	7.99	17.12	95.04	9.64	104.7
Case-3 80% MSW+20% Coal	39.87	9.16	12.49	176.00	25.96	201.95	23.90	10.53	17.27	84.48	19.28	103.8
Case-4 70% MSW+30% Coal	36.95	11.13	13.26	154.00	38.94	192.93	21.71	13.12	17.42	73.92	28.91	102.8
Case-5 60% MSW+40% Coal	33.75	13.29	14.02	132.00	51.93	183.91	19.48	15.75	17.58	63.36	38.55	101.9
Case-6 50% MSW+50% Coal	30.22	15.68	14.78	110.00	64.91	174.89	17.21	18.43	17.74	52.80	48.19	101.0
Case-7 0% MSW+100% Coal	5.20	32.60	18.59	0.00	129.81	129.81	5.2	32.6	18.59	0	96.4	96.4

Table 5: Gaseous emissions estimated per tonne of MSW and coal.

Blending proportions of MSW and Coal	MSW including food waste					MSW excluding food waste				
	Excess air (tonnes/d)	CO_2 (kg/d)	SO_2 (kg/d)	NO_x (kg/d)	Ash (kg/d)	Excess air (tonnes/d)	CO_2 (kg/d)	SO_2 (kg/d)	NO_x (kg/d)	Ash (kg/d)
Case-1 100% MSW+0% Coal	7.76	1,817.8	2.40	172.7	57.0	8.91	2,000.7	3.40	92.1	55.0
Case-2 90% MSW+10% Coal	7.80	1,821.6	2.87	165.0	73.5	8.84	1,989.5	4.01	87.9	79.9
Case-3 80% MSW+20% Coal	7.85	1,825.8	3.38	156.6	91.6	8.77	1,978.2	4.63	83.7	105.3
Case-4 70% MSW+30% Coal	7.89	1,830.3	3.93	147.4	111.3	8.69	1,966.6	5.26	79.4	131.2
Case-5 60% MSW+40% Coal	7.94	1,835.3	4.55	137.2	132.9	8.62	1,954.9	5.90	75.0	157.5
Case-6 50% MSW+50% Coal	7.98	1,840.7	5.22	126.1	156.8	8.55	1,942.9	6.55	70.6	184.3
Case-7 0% MSW+100% Coal	8.20	1,879.6	10.00	47.0	326.0	8.20	1,879.6	10.00	47.0	326.0

alone is not an option for the generation of power, the calculations mentioned show the bare minimum amount of profit/gain which is expected from the business of waste-to-energy. In real life situations, MSW is to be blended with coal for getting the consistency in power generation. In any of the blending proportions, the waste-to-energy plants will have a minimum profit of Rs. 0.18 million/day (Table 6, MSW excluding food waste) and the pay back time can be estimated from the installation costs. The ash produced as a by-product will also have monetary benefits.

Furthermore, if the segregated food wastes from the MSW is used in either of biomethanation or composting, there will be additional benefit in methane generation (for power utilities) or manure. Also, the MSW excluding food waste generates lower NO_x emissions (Table 5) than the MSW including the food wastes, and the separation also saves the hydrothermal processing costs (pre-heating and drying) associated with food wastes. The byproducts of biomethanation include biogas and nutrient rich manure. Biogas produced can be utilized for electricity generation and the manure can be used for farming. According to the experience of Pune city's Municipal Corporation, a net profit of Rs. 0.2 million per year can be obtained from 1 tonne per day of food waste (Pathak 2013). Proportionately the net profit for

Table 6: Cost-benefit analysis of power generation by using coal and MSW.

Operations	MSW including food waste		MSW excluding food waste	
	Case-7 100% Coal (Million Rupees per day)	Case-1 100% MSW (Rupees per day)	Case-7 100% Coal (Rupees per day)	Case-1 100% MSW (Rupees per day)
Cost incurred for fuel	0.39[a]	0	0.29[a]	0
Cost incurred for collection & transportation	0.06[b]	0.9[c]	0.05[b]	0.9[c]
Cost incurred for O&M of plant	0.13 [d]	0.6[e]	0.1[d]	0.44[e]
TOTAL COST (a)	0.58	1.5	0.44	1.34
Returns from sale of power (b)	2.0[f]	2.0[f]	1.52[f]	1.52[f]
NET GAIN (b-a)	1.42	0.5	1.08	0.18

[a] Cost of coal per tonne: Rs. 3,000 (Rs. 2260 + Misc. charges + 5% Tax) of grade G-10 of Singareni Collieries Company Limited (SCCL 2017)
[b] Cost of transportation per tonne of coal for 160 km from mine site to Warangal city: Rs. 450 by railways (Indian Railways 2018)
[c] Integrated Solid Waste Management data from Warangal city (ISWM 2016)
[d] NPTC Thermal power plant data (Mittal et al. 2012)
[e] Bawana Waste-to-Energy plant at Delhi (Jain et al. 2014)
[f] Cost of unit power: Rs. 3.8 @ 1 kWh (TSERC 2016)

Table 7: Evaluation of different blend proportions of coal and MSW, in terms of volume reduction and air quality.

Blending proportions of MSW and Coal	MSW including food waste				MSW excluding food waste			
	Treatment of MSW or volume reduction (V) $V_i=MSW_i/MSW_{max}$	NO_2 $N_i=(1-NO_{2i}/NO_{2max})$	SO_2 $S_i=(1-SO_{2i}/SO_{2max})$	Score (max=3) $Score_i=V_i+N_i+S_i$	Treatment of MSW or volume reduction (V) $V_i=MSW_i/MSW_{max}$	NO_2 $N_i=(1-NO_{2i}/NO_{2max})$	SO_2 $S_i=(1-SO_{2i}/SO_{2max})$	Score (max=3) $Score_i=V_i+N_i+S_i$
Case-1 100% MSW+0% Coal	1.00	0.00	0.76	1.76	1.00	0.00	0.66	1.66
Case-2 90% MSW+10% Coal	0.90	0.04	0.71	1.65	0.90	0.05	0.60	1.55
Case-3 80% MSW+20% Coal	0.80	0.09	0.66	1.55	0.80	0.09	0.54	1.43
Case-4 70% MSW+30% Coal	0.70	0.15	0.61	1.46	0.70	0.14	0.47	1.31
Case-5 60% MSW+40% Coal	0.60	0.21	0.55	1.36	0.60	0.19	0.41	1.20
Case-6 50% MSW+50% Coal	0.50	0.27	0.48	1.25	0.50	0.23	0.34	1.07
Case-7 0% MSW+100% Coal	0.00	0.73	0.00	0.73	0.00	0.49	0.00	0.49

Warangal city will be added to Rs. 23 million per year (Rs. 0.063 million/day) with generation of 115 tonnes per day of food waste. Our estimates show that with the addition of added gains from biomethanation, the minimum assured profit increases to Rs. 0.24 million/day (sum of Rs. 0.18 million and 0.063 million).

Further, the scores obtained from the objective function for various blends and scenarios of MSW and coal show that, it is optimum to consider 90 to 80% of MSW (including or excluding food waste) and 10 to 20% of coal. The cases-2 and 3 in both the scenarios of MSW have the scores in the range of 1.65 to 1.43 (out of maximum score 3), which are obtained by considering the factors of waste volume reduction and lower gaseous emissions (Table 7).

Specific to our study, the results show that co-firing MSW including food waste seems profitable by Rs. 0.26 million per day compared to MSW excluding the food waste. However, the costs involved in hydrothermal treatment of the MSW including food waste and also costs involved in segregation of food waste would actually determine the overall profitability. Further, production of manure out of food waste in opting biomethanation process will enrich the nutritional value of wastes and it can be helpful for organic farming and thereby the dependence on chemical fertilizers can be reduced.

CONCLUSIONS

Waste-to-energy is being practiced worldwide to overcome the energy demands and to efficiently process the municipal solid wastes in urban areas. Incineration is the well known and proven thermo-chemical process for energy generation from solid wastes. Particularly, as MSW is inconsistent in composition and quantity, it needs to be blended with auxiliary fuels such as coal for making up the generation of constant amount of power. Our study characterizes the MSW of Warangal city and suggests that the waste can be suitably blended with 10-20% of coal for sustainable operation of waste-to-energy plants. Also, the cost benefit analysis shows that by operating the waste-to-energy plants a net gain of Rs. 0.18 million /day can be obtained. Urban management authorities in many Indian cities are facing a challenge of growing MSW and similar studies will help the authorities to plan a suitable technological solution for better management of the waste. Hence, the overall life cycle of MSW and its associated benefits will certainly prove its sustainability in a much wider scope of analysis. And we strongly suggest for an extension of this study with a complete life cycle assessment of waste utilization and added benefits in terms of reduction in GHGs, reduction in chemical fertilizers, waste utilization, aesthetics, improvement in health and much more.

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