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Research Article

Experimental analysis for thermodynamic characteristics of municipal solid waste for energy generation with environmental and economic assessment in Indian scenario

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ABSTRACT

Excessive energy use has caused a disturbance in the planet's life support system. It has created an adverse impact on water and natural resources. Power generation from solid waste can be an alternative to reduce waste volume and has an extra advantage in cleaning the surrounding with the gain of electric power supply. Innovative technologies and future perspectives of MSWI were highlighted. Moreover, the latest understanding of immobilization mechanisms and advanced characterization technologies were elaborated to foster the future design of treatment technologies and the actualization of sustainable management for MSWI. Solid waste to energy conversion provides economic and atmospheric benefits by introducing renewableenergy sources at minimum environmental influences.This analysis has focused on MSW to energy conversion system by incineration technique to generate electricity along with other bi-product and determines the system's financial feasibility. The experiment has been conducted to calculate the physio-chemical characteristics of municipal waste with a bomb calorimeter and incinerator for electricity generation. Solid waste characteristics like chemical exergy, entropy, higher heating point, energy flux, and potential have been analyzed for the incineration technique's viability.The thermal properties have been analytically described in the experiment. The result shows that MSW has a higher calorific value of 8.5-12.5 Mega Joule/kg, and charcoal has a higher calorific value of 27-32 Megajoule/kg.It also analyses that one-ton MSW can produce 600 kWh electricity with 360 gm CO_2-eq/kWh generation.

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INTRODUCTION

Solid Waste as a Fuel

Waste-to-energy plants reduce the municipal solid waste volume by about 90%. The generated combustion energy is regarded as renewable energy and is typically used to feed a turbine to generate electricity.In developing countries, technology is being applied using municipal solid waste to generate electrical power, heating energy, biogas,fertilizer, etc.

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[1]. The shifting, storage, and garbage station monitoring of municipal solid waste in developing countries is continued in the progressive phase [2]. Approx.1600-1700 tons of RDF is generated in developing countries per day.RDF can quickly generate biogas and heat in developing countries by compressing solid waste for incineration [3]. Solid wastes to energy conversion technologies are crucial to be adopted by the municipal corporation to accommodate the expanding economic requirement for the plant installation, operation, and maintenance.An E-smart, MSW storage arrangement minimizes the solid waste with two, three, and four Underground column bins [4]. Developing countries are focusing on suitable waste-to-energy technology for energy generation. Various physio-chemical and thermal properties of MSW have been analyzed [5].The WtE process of MSW for the techno-economic analysis has been discussed [6].

The WtE process provides the advantage of utilizing the solid waste system globally and green power production like bio-gas, syngas, etc. [7]. MSW amount has decreased in proportion due to recycling process[8].Electrical power can also be produced from MSW,reducing the dependency on natural fuels [9]. The effect of CO, CO_2 and harmful gases can be minimized by avoiding the contaminated gas emission. It is feasible to provide unused energy from mixed waste without affecting the atmosphere and support the country's continual progress [10]. This work offers a complete exergy analysis of the municipal solid waste incineration process [11]. Thermo-chemical conversion method has good prospects with reasonable calorific value for conversion into power energy [12]. The major factor of adopting WtE technology is to focus on minimization of solid waste, getting valuable bi-products, and generating electrical power. Hence the general objective of this work is:

(i) Find out the moisture water percentage, variable matter, and residual percentage of municipal solid waste
(ii) Determine the calorific value of waste experimentally using a bomb calorimeter
(iii) Estimation of municipal waste's potential for electricity generation to minimize solid waste by eradicating pollutants.

Research in this area

Shackley et al. executed the study on CO_2 consumption from solid waste stock and established that many researchers confirmed the same matter within the area for the carbon dioxide moderation system [13]. Wolsink indicated that society participants in the development phase would be beneficial to buildup the guideline for social behavior, which will not be feasible for civil realization [14]. Communication gaps are the main reason for adopting the energy recovery process for disposal and utilization. The main cause of civilian opposition to the renewal power technique was defined by Rogerset al. [15].

With many power production processes by Dong et al., 2003 [15], getting power from solid waste is an advantage. Solid waste system obligation in China and solid waste operation, grouping, storage, price, time, and learning effect for solid waste resolution by Wang et al. [16]. Abu-Qudais and Abu-Qdais, 2000 have analyzed the work and system in the metro cities of solid waste that can provide different atmospheric complications [17]. Landfilling is a general trend of solid waste dumping. The present disposal areas in the world generally are not properly well managed, as discussed by Ogwueleka 2009 [18]. Contaminates are discharged from the dump area, ultimately affecting civilian health and life. To determine the heating value of municipal solid waste for perfect technique and waste to energy transformation technology by Akkaya and Demir, 2009; [19] Kalantarifard and Yang, 2011 [20].

Research gap

Earlier research has focused on the waste-to-energy conversion process after manual segregation of inorganic and organic compounds.Solid waste generates energy and heat from the energy source, making non-dependency on fossil fuels and gas emissions the leading cause of pollution(Chinwan and Pant, 2014) [21]. This technology is convenient as it contains suitable organic composition, moisture content (range 10- 20% each), and calorific value (range 1000-1700 kcal/kg) without segregation.Waste generation isthe main issue on the earth due to greenhouse gas (GHG) emissions (Ithraa, 2016) [22]. This is a prime concern to install emission control equipment in the incinerator to control the emissions [23]. Incineration is a waste treatment technology in which waste mass is reduced by 70%, and waste volume is reduced up to 90%. In municipal solid waste management, produced heat energy is converted into electricity generation, as discussed by Gupta et al., 2017 [24].

The presented system has an automated segregation technique of inert substances like construction material and solid waste for incineration. It will save time and system economic viability for the process.The proposed research uses high-rise chimneys and filter bags to minimize the impacts on human health and the atmosphere. This system is feasible at a higher volume rate [25]. The design philosophy and feasibility of the incineration-based solid waste to electrical conversion system havebeen developed based on the physio-chemical properties of solid waste.

METHODOLOGY

Solid waste is material the primary user cannot reuse for recycling, reproduction, transformation, conversion,or disposal for utilization [26]. The solid waste incineration system produces heat and power as energy substitutes [27]. The higher calorific value of solid waste is used for power production precisely after sorting, segregation, or conversion processes [28]. The methodology consists of recycling and composting, combustion with energy recovery, landfilling evaluating life cycle, tipping fee, and internal rate of return [29]. The incinerator plant generates energy and heat from municipal solid waste for domestic and industrial

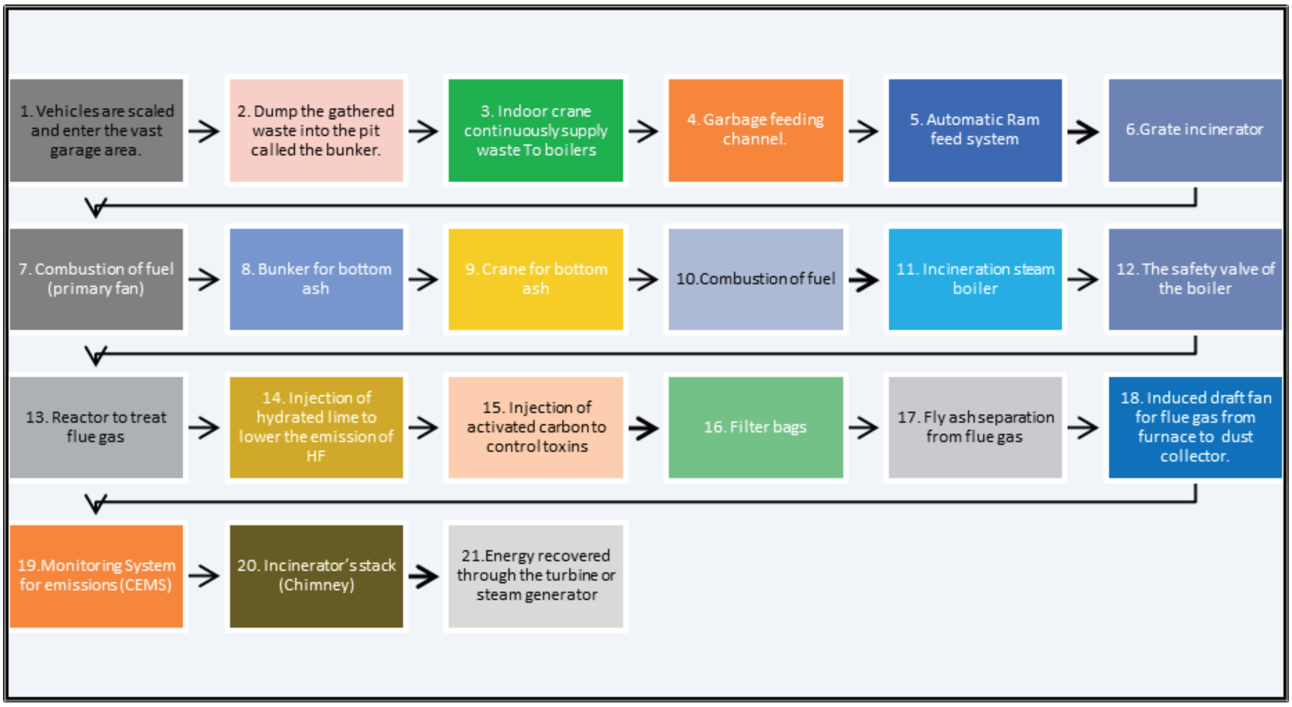

Figure 1. Incineration process of municipal solid waste for electrical energy generation.

use to solve the solid waste storage problem [30]. Figure 1 shows MSW's latest incineration process flow with flue gas cleaning containing 21 sub-components. In fact, most of the electrical power generated by incineration is supplied to the grid with suitable voltage and frequency via a transmission system [31].

The generated electrical power is a plant byproduct sold as base load generation.Due to the unknown waste composition and stringent environmental standards, waste-to-energy plants employ sophisticated flue gas cleaning devices for emission control. MSWI system has the following intelligent E-smart sub-components.

Electrical System

The electrical system configurations with aspects of safety,efficiency, and conformity with international standards include:

i) Unitand auxiliary transformers
ii) Substation control, recording, and protection systems
iii) Backup supply network, including emergency power and auxiliary power supplies
iv) High-speed transfer systems, motors, and frequency converters
v) Synchronization, excitation, and automatic voltage control systems
vi) Substation control systems

Control System

Development of power plant control systems with improving cost-effectiveness, functionality, and quality has been added. The advantages of this control solution are:

i) A future-oriented platform for process and electrical systems
ii) Easy-to-use and consistent user interface
iii) Fast analysis of disturbances and enterprise-wide access to information
iv) High engineering efficiency, quality, low operating and maintenance costs

Electrical Equipment

These include:

i) Connections to the public grid,including generator leads and generator connections
ii) Switchgear for all voltage levels, including the associated circuit breakers and other switchgear
iii) Unit and auxiliaries transformers, substation control,recording and protection systems
iv) Backup supply network, including emergency power and auxiliary power supply
v) Frequency converters and motors

Control Equipment

It includes the instrumentation, electrical control equipment, boiler protection system, and operation management into an overall concept and creates a technically optimized full-scale solution. Figure 2 shows the process of e-system for incineration of MSW including all sub-components.The specific requirements regarding the implementation were identified:

i) User-friendly and consistent user interfaces
ii) Plant-wide and company-wide easy access to information
iii) A highlevel of engineering quality and efficiency

iv) Low operating and maintenance costs
v) Clear system architecture with state-of-the-art technology

E-Instrumentation for Incineration System

This section covers:

i) Instrumentation for pressure,differential pressure,-flow rate and filling-level measurement
ii) Temperature measurement
iii) Water/Steam and Fluegas analyzers
iv) Emission measurement computer

Various WTE Methods/Technology

There are mainly three waste-to-energy transformation systems in the present scenario.There are various types of incinerator plant design. 1-Fixed or moving grate combustion. 2-Rotary-kiln. 3-Fluidized bed. Thermo-chemical conversion is characterized by high transformation rates and less water content of feed stock frequently not chosen for solid waste [32]. The biochemical transformation system involves anaerobic digestion and fermentation suitable for high carbonic compounds and more watered solid waste. The physio-chemical technique includes different processes to improvise the physical properties of municipal waste [33].

Sample Analysis of MSW

Solid waste component has been analyzed for burning in the combustion chamber. Paper and food have a big part in the waste,producing more heat on combustion in the chamber. Thermal treatment of solid waste by combustion has been preferred to dispose of municipal waste for generating electricity in India [34]. Table 1 and Figure 3 analyze solid waste components and percentage values utilized in the incineration process. It contains bio-degradable and non bio-degradable wastes. The negative effect of non-treatment of MSW is various deceased to human and temperature rise in the environment. In others, MSW components include construction material, electronic waste, the chemical mixture of silt, etc.

Table 1. Average MSW compositions in developing countries

Sl no.	MSWComponent	Percentage (%)
1	Paper Textile	27.5
2	Leather and Rubber Wood	9.2
3	Plastic	6.2
4	Metals	8.8
5	Glass	9.1
6	Yard Trimmings	4.5
7	Food	28.5
8	others	6.2

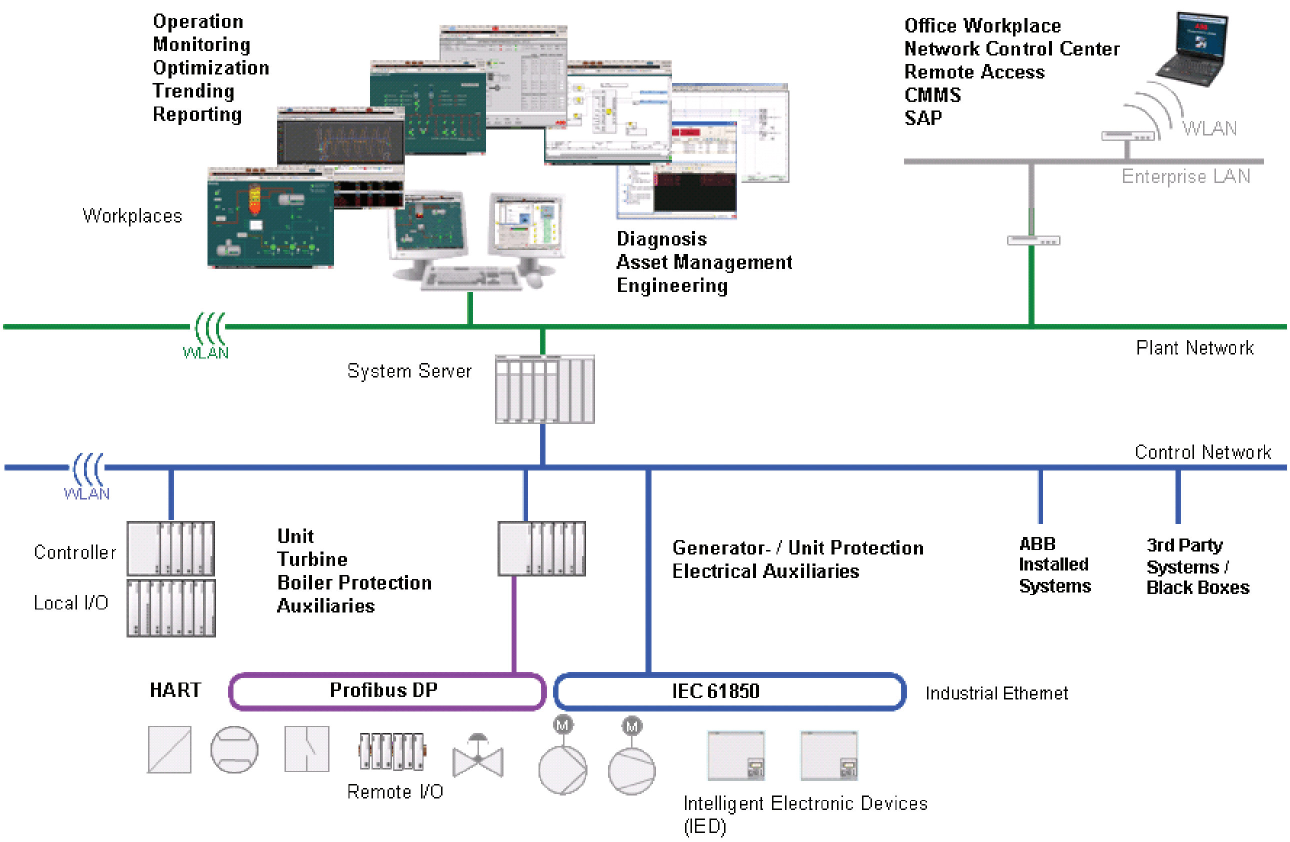

Figure 2. E-Instrumentation System for incineration of MSW.

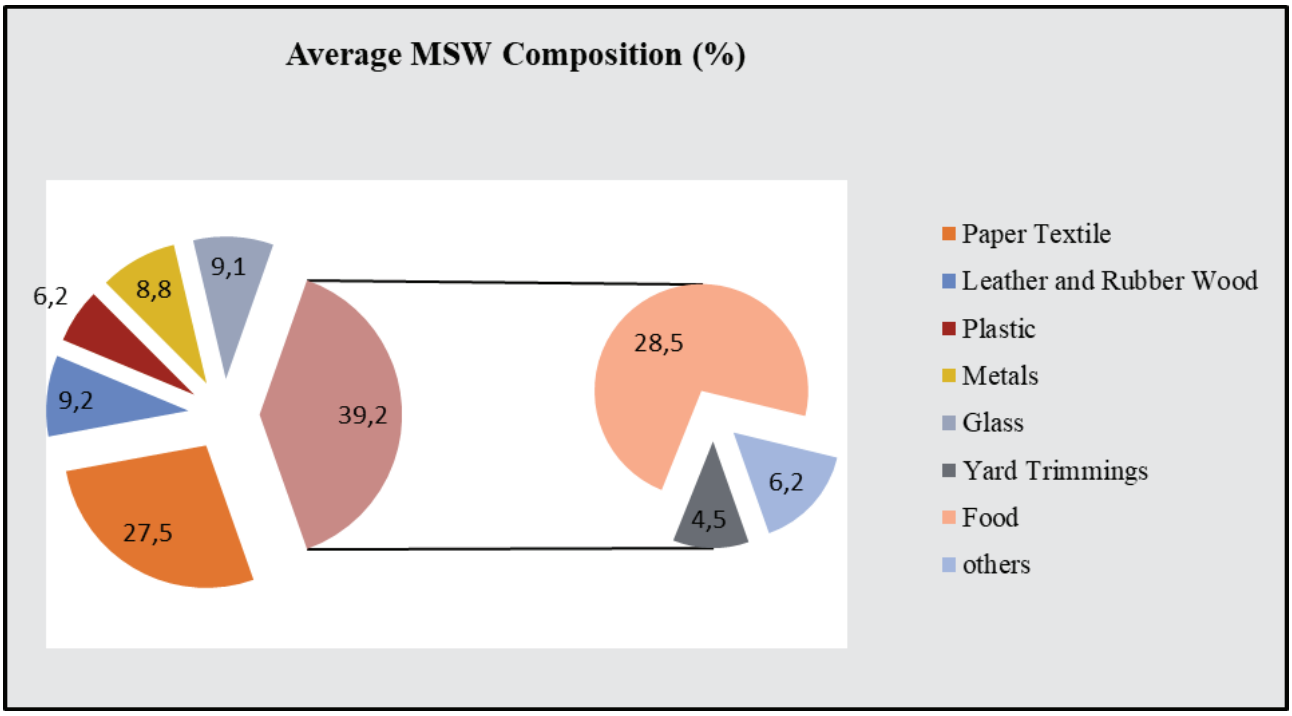

Figure 3. Component analysis of municipal solid wastein developing countries.

Proximate Study

The comparative study gives the water content, variable content, free carbon, and residual in the experimental sample for thermal utilization of solid waste [35]. The experiment has been arranged according to the ASTM system. Bulk density and durability were found in 314–467 kg/m^3 and 88–99.25% [36]. Table 2 and Figure 4 compare the collected data for the proximate & ultimate analysis of solid waste.

Water content analysis

Water content in the solid waste was analyzed with 500 g(W)as a dry sample in a scientific digital microwave oven at 105°C for 24 hours to a constant weight of 415.8g (W1). The sample is again dried in a microwave oven for 24 hours at 550°C, and the weight is found at 245.5g (W2). The water moisture content (WMC) is determined in the form of weight loss in the experiment as given below:

Water moisture content in percentage =

$$\left\{\frac{W-W1}{W}\right\} \times 100 \quad (1)$$

The percent volatile matter content (VMC) is calculated as given below:

Volatile Matter content percentage =

$$\{(W1 - W2)/W1\} \times 100 \quad (2)$$

Ash content percentage = [{(mass of vessel+ lid+ ash) - (mass of vessel+ lid)} / mass of sample] x100

Fixed carbon

The carbon value in the ash sample was determined using the given formula:

$$FC\% = 100 - (MC + ash + VMC) \quad (3)$$

Table 2. Proximity analysis (Proximate & Ultimate)

Sl no.	Characteristics	Experiment Result (%)
A	**Proximate study**	
1	Water content (Moisture)	16.84
2	Variable Matter	53.70
3	Ash	21.80
4	Fixed Carbon	7.66
B	**Ultimate study**	
1	Carbon	29.59
2	Hydrogen	2.35
3	Oxygen	11.95
4	Sulphur	0.81
5	Nitrogen	0.89
6	Chlorine	0.08
7	Mineral Matter	54.33

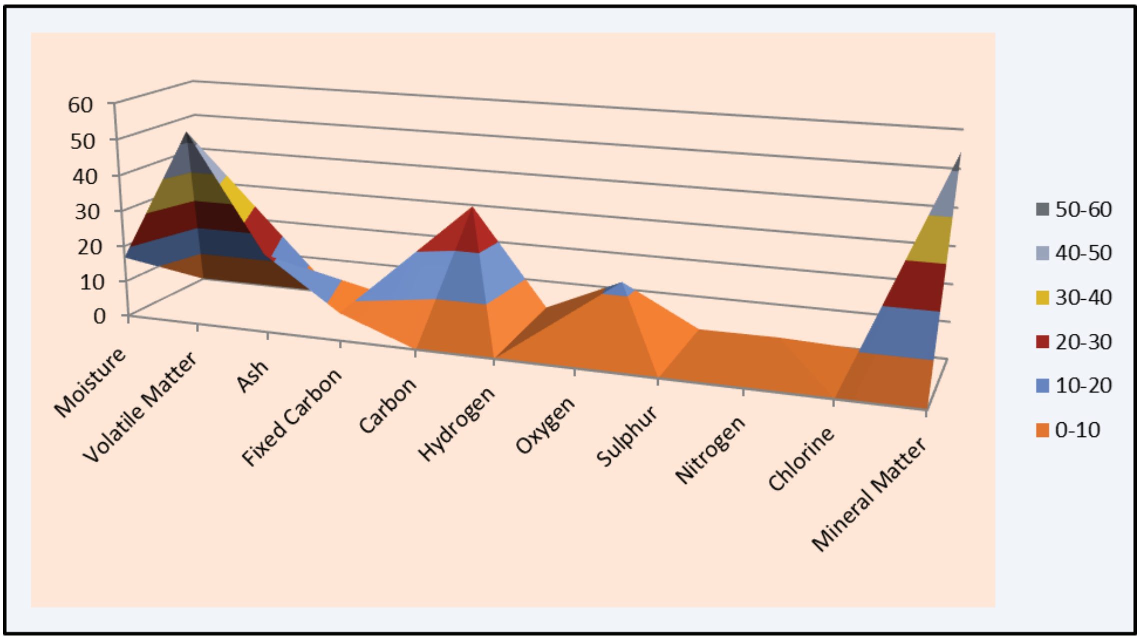

Figure 4. Proximate analysis of MSW for various components.

Determination of Calorific Value

This analysis has utilized a volatile portion of solid waste. A sample of 1000 gramshas been considered from volatile matter after isolating non-volatile matters. It has been stored in a microwave oven for 24 hrs under 105°C to calculate the water content. The dehydrated sample has been minimized using a blender and isolated using a one mm sieve for achieving full ignition in the Bomb Calorimeter instrument to measure the calorific value of MSW, as shown in Figure 5. It consists Barometer, Compressor m/c, Vessel, Stirring rod, and voltmeter. The sample was heated with purified oxygen in a closed vessel. Heat energy was given off, measuring the temperature rise in the crucial and circumferential surface in the WtE assessment [37]. The analysis has shown the calorific values obtained from the experiment were 16.098, 18.957, 38.848, and 10.968 MJ/kg

Figure 5. Bomb calorimeter apparatus for calorific value measurement of MSW.

Table 3. Average calorific value of MSW components in developing countries

Sl no.	MSW Components	Average Calorific Value (KJ kg^{-1})
1	Putrescible	16098
2	Paper	18957
3	Plastic	38848
4	Textile	10968

for putrescible, paper, plastic, and textile waste, respectively. The average calorific value of MSW components in MJ/kg has been tabulated in Table 3 and Figure 12. Plastic has the highest value of 38.848MJ/kg, and textile has the lowest value of 10.968 MJ/kg.

$$W = \{\varepsilon\Delta T\text{-}\emptyset\text{-}V\}/MW \tag{4}$$

Where W= calorific value (kJ kg^{-1}), ε =bomb calorimeter (XR-IA) standardization= Temperature difference (°C), Ø= fuse wire correction (3.2), V= acid correction (m^3), and M= mass of sample (kg)

EXPERIMENT

In the present scenario, MSW is generating continuously world wide. A large amount of solid waste is suitable for energy recovery [38]. Solid waste with moisture percent is the primary waste factor in energy conversion technology.

The solid waste incinerator system for thermal characteristics has been analyzed in this experiment.Figure-6 shows the demonstration details of the model system for incineration solid waste. It contains mainly pyrolysis and combustion vessel, vessel cover, high-pressure air blower, heat recovery, hot water feeds, gas vent pipe,liquid drain,ash drain, boiler, and water storage. The operating steam pressure of 10 bars with a 500 Kg/hr fuel consumption rate is utilized for mass-burn incineration. This model can be used as an alternative for electricity generation by incinerating rural and urban solid wastes. With the help of Dulong's formula, the energy value of the solid waste composition is 13105 Kilo Joule/kilogram. The furnace is heated by energy in the combustion vessel up to 870.8°K, and the mass of air volume recorded at 8.70 kg.

Combustion Firing Process of Solid Waste

The grate-fired combustion of a heterogeneous mixture of solid waste material involves drying and degassing followed by pyrolysis and gasification. The energy released is utilized in the Rankine cycle to produce heat and energy. It has been designed to combust solid waste fuel without the need for major pre-treatment, which is placed on top of a grate with primary air passing through it and secondary air passing over it. This technology is comprised of a stoker or fuel support feeding system, a grate assembly to burn the fuel, an under-fire or primary air beneath the grate, a

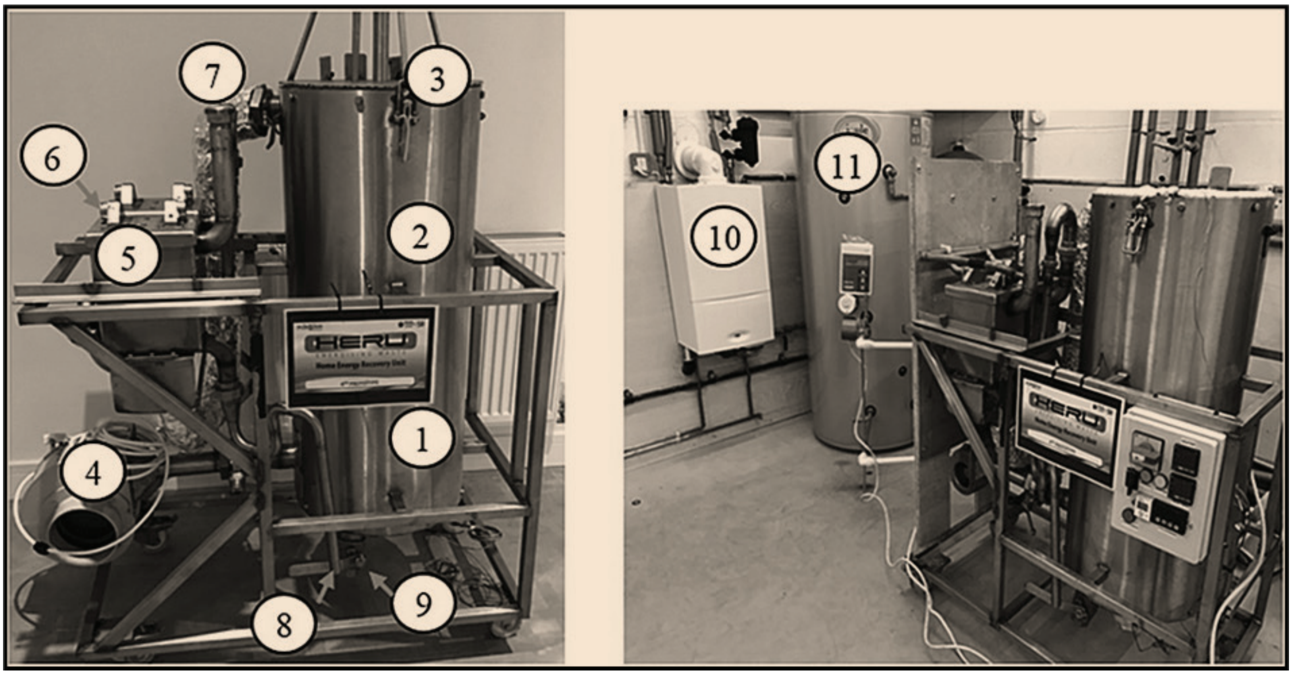

Figure 6. Instrument for incineration of solid waste1.Pyrolysis vessel 2. Combustion vessel 3. Compressors cover 4. High pressure air blower 5. Heat recovery 6. Hot water feed system 7. Gas vents pipe 8. Liquid drain 9. Ash drains 10. Boiler 11. Water tank for storage.

Figure 7. Inside view of the solid waste combustion chamber by the infrared camera.

secondary air system to support the ignition process, and controlled atmospheric radiation of gas an ash discharge system of energy [39]. The combustion process of waste with the help of an infrared camera has shown in Figure 7.

The main process parameters for the incineration process of municipal solid waste are shown in Table 4.

With the use of Dulong's formula for estimating the produced energy, municipal waste has been given here:

$$\text{Dulong's Formula} = 338.2 \times C + 1442.8 \times (H - O/8) + 94.2 \times S \quad (5)$$

Where C=Carbon H = Hydrogen O = Oxygen S = Sulphur,

Steam power energy generally contains 48% of heat energy. This supports moving the turbine to generate electrical power. Therefore, the electrical energy generated = Steam power/Electrical power = 6245.05/ 11042.95 = 0.5655 kWh/kg = 565.5 kWh/ton.

Performancemonitoring for Plantoptimization

E-smart system continuously compares the actual plant performance to expected performance. This may include the online calculation of the waste calorific heat for operator support and automated control system responses. Combustion optimization solutions use predictive control techniques to reliably find the most suitable set points for improving the heat rate and reducing emissions like NOx.

Emission monitoring

For emission monitoring, it consistsof:

i) Design according to local authority requirements
ii) Selection of suitable instruments from the incineration system
iii) Considering proper flue gas extraction and sensor location
iv) Calibration according to certified measuring standards
v) Emission monitoring reports according to international norms
vi) Structuring the existing control system solutions
vii) Option for switching off the existing set point controls
viii) Integratingthemulti-variablecontrollerandmatching with theplant

Chemical Exergy of Solid Waste

The chemical exergy of the fuel is a fundamental property of the energy conversion process. The chemical exergy

Table 4. Process parameters for incineration of municipal solid waste in developing countries

Characteristics	Measured value
Temperature range	820°C-980°C
The recovery rate of Organic substances	60-79% (98% at a temp of 1550 degree Celsius)
Net calorific value	>13000 kJ/kg
pH of ash	11.4
The moisture content of ash	1.65 %
Bulk density (kg /m^3)	1277.6
Expected energy generation	565.5 kilowatt hour per ton from solid waste
Residualash content	Up to 15-30%

is the same as the highest value of work that can be achieved after heating the component. Solid waste is a heterogeneous substance with a complex structure lacking an exact chemical exergyvalue [40]. All values are assumed at the standard temperature T^0 = 298.15 ^0K and standard pressure P^0 = 101.325 kPa. Figure 10 has analyzed the comparison of chemical exergy and entropies of different substances.

$$\text{Plastic waste: } eP = 376.89C + 787.35H - 58.65O + 46.40N - 1533.26S + 100.98Cl \quad (6)$$

$$\text{Textile/Rubber waste: eTR} = 376.57\text{C} + 790.87\text{H} - 58.48\text{O} + 44.64\text{N} - 1538.19\text{S} + 98.57\text{Cl} \quad (7)$$

$$\text{Wood log/Paper sheet waste } eWP = 374.64\text{C} + 806.34\text{H} - 57.07\text{O} + 48.69\text{N} - 1533.26\text{S} + 101.43\text{Cl} \quad (8)$$

$$\text{Food waste } eF = 377.54\text{C} + 785.72\text{H} - 58.45\text{O} + 45.69\text{N} - 1536.25\text{S} + 103.49\text{Cl} \quad (9)$$

$$\text{Mixed solid wastee MSW} = 376.47\text{C} + 791.02\text{H} - 57.82\text{O} + 45.47\text{N} - 1536.24\text{S} + 100.98\text{Cl} \quad (10)$$

In the experiment, the lower, higher, and mean specific exergy values of municipal solid waste have been calculated as 16610 kJ/kg, 38856 kJ/kg, and 21538 kJ/kg, respectively. By these data average,the specific chemical exergy of municipal solid waste is 25668 kJ/kg. The specific exergy of plastics matter, textile cloths/rubberized, wooden/paper sheets, residual food, and waste mixtures have been calculated as 25612.19 kJ/kg, 24539.36 kJ/kg, 22462.23 kJ/kg, 22101.47 kJ/kg, 22512.19kJ/kg, respectively.

Determination the Higher Heating Value of Solid Waste

There are six categories of flammable solid waste: food, wooden, paper sheet, textiles, cloths, plastics, and rubberized items. The correlation equation having low error and maximum coefficient of evaluation is selected. Table 5 and Figure 11 compare thehigher heating value of municipal solid wastecomponents. The maximum HHV of plastic waste is 217.41 kJ/kg, and the minimum HHV of food waste is 51.48kJ/kg.

HHV for plastic waste

$$\text{eP} = 376.88\text{C} + 787.35\text{H} - 58.65\text{O} + 46.39\text{N} - 1533.26\text{S} + 100.98\text{Cl (kJ/kg)} \quad (11)$$

HHV for textile/rubber waste

$$e\text{TR} = 376.58\text{C} + 790.87\text{H} - 58.48\text{O} + 44.64\text{N} - 1538.19\text{S} + 98.57\text{Cl (kJ/kg)} \quad (12)$$

HHV for wooden/paper sheet waste

$$e\text{WP} = 374.65\text{C} + 806.35\text{H} - 57.08\text{O} + 48.70\text{N} - 1533.27\text{S} + 101.46\text{Cl (kJ/kg)} \quad (13)$$

HHV for food waste

$$eF = 377.54\text{C} + 785.70\text{H} - 58.45\text{O} + 45.69\text{N} - 1536.25\text{S} + 103.49\text{Cl (kJ/kg)} \quad (14)$$

HHV for mixed waste

$$e\text{msw} = 376.47\text{C} + 791.02\text{H} - 57.82\text{O} + 45.47\text{N} - 1536.24\text{S} + 100.98\text{Cl (kJ/kg)} \quad (15)$$

Table 5. Higher heating value of municipal solid waste

Sl no.	Waste components	Higher heating value (kJ/kg)
1	Plastic Waste	217.41
2	Textile/Rubber waste	205.95
3	Wood/Paper waste	77.74
4	Food waste	51.48
5	mixed Waste	97.66

Entropy Determination of Solid Waste

Solid waste includes carbonic compounds in plastic, wooden logs, paper sheets, textile/cloths, and rubberized food items. First-order polynomial or the standard correlation has been used for carbonic compound entropy. The"first order polynomial Chang correlation equation" has been used to find the generalized entropy of mixed solid waste components.

Entropy for plastic wastes

$$\textit{entropy for plastic waste } (s0PL) = 0.0088C + 0.0754\text{H} + 0.0135\text{O} + 0.0078\text{N} + 0.0085\text{Cl kJ/°K} \quad (16)$$

Entropy for textile clothes/rubberized waste

$$\textit{entropy for Textile or rubberized waste } (s0TR) = 0.0098\text{C} + 0.064\text{H} + 0.013\text{O} + 0.014\text{N} + 0.017\text{S kJ/°K} \quad (17)$$

Entropy for wooden/paper sheet waste

$$\textit{entropy for wooden or papaer sheet waste } (s0WP) = 0.0165\text{C} + 0.0117\text{H} + 0.0082\text{O} + 0.00695\text{Cl kJ/°K} \quad (18)$$

Entropy for food waste

$$\textit{entropy for food waste } (s0F) = 0.0066\text{C} + 0.081\text{H} + 0.013\text{O} + 0.011\text{N} + 0.011\text{S kJ/°K} \quad (19)$$

Entropy for mixed solid waste

$$\textit{entropy for mixed solid waste } (s0MSW) = 0.011\text{C} + 0.064\text{H} + 0.0108\text{O} + 0.0109\text{N} + 0.0156\text{S} + 0.0085\text{Cl kJ/°K} \quad (20)$$

The above analysis indicates that the entropy result of solid waste is more precious than standard values. Table 6 has tabulated the standard entropy of solid waste components. Plastic waste has a maximum value of 0.0135 kJ/°K, and mixed waste has a minimum value of 0.00654kJ/°K

Table 6. Entropies of solid waste components

Sl no.	Solid waste components	Standard entropy(kJ/°K)
1	Plastic Waste	0.0135
2	Textile/Rubber waste:	0.00834
3	Wood/Paper waste	0.0124
4	Food waste	0.00804
5	Mixed Waste	0.00654

The higher heating value, standard entropy, and exergy of solid waste are presented in equations, respectively.

$$\textit{Higher heating value } (HHV) = 0.365C + 0.864H - 0.076O + 0.029N - 1.634S + 0.063Cl\ (KJ/kg) \quad (21)$$

$$\text{standard entropy } (S°MSW) = 0.011C + 0.065H + 0.0108O + 0.0109N + 0.0160S + 0.0085Cl \quad (22)$$

$$\textit{exergy of solid waste } (eMSW) = 376.465C + 791.020H - 57.820O + 45.475N - 1536.245S + 100.983Cl \quad (23)$$

In Table 7, Higher heating value, standard entropy(S^0_{msw}), and exergy of solid waste ($e_{msw)}$ have been calculated as above, and it has been estimated 0.1005(MJ/kg), 0.00364(kJ/K kg), and 135.175(kJ) respectively.

RESULT ANALYSIS

From the analysis, the physio-chemical properties have been identified. The calorific value of mixed solid waste components has been determined. In contrast, renewal energy sources have only one percent contribution. This share is to be increased by implementing the waste-to-energy recovery system for power generation. Incineration has an advantage over other processes for mixed solid waste.

Table 7. Properties of MSWin developing countries

Sl no.	Properties	Value
1	HHV (higher heating value)	0.1005(MJ/kg)
2	S^0_{msw} (standard entropy)	0.00364(kJ/°K)
3	e_{msw} (exergy of solid waste)	135.175(kJ)

Energy Flux Supplied to the Incinerator

The energy flux was supplied by combing natural gas and the air for combustion in the incinerator. The flux value is varied from 120.8kW to 1220.6 kW. The mean value of the chemical enthalpy flux waste was 670.7kW. The energy flux as natural gas (secondary fuel) fluctuated from 115.8 kW to 828.0 kW, reaching an average value of 471.9 kW. The average temperature in the combustion chamber was 815°C during the testing period. The temperature of air used for the solid waste combustion oscillated between 87.6°C and 125.6ºC. The enthalpy flux of air varies between 7.8 kW and 105.5 kW. The temperature of the air fluctuated between 26.2°C and 32.8°C. The enthalpy flux in air does not exceed 2.9kW. Figure 8 compares the flux of chemical enthalpy for air and combined flux supplied to the incinerator with time.

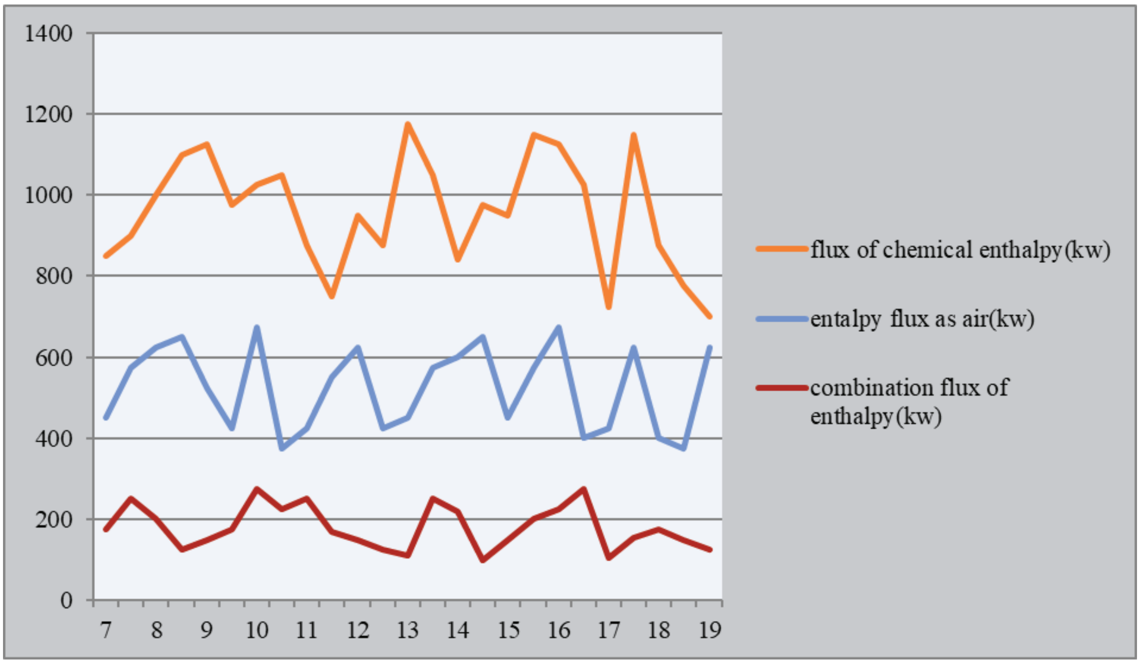

Figure 8. Energy flux of chemical enthalpy for air and combined flux supplied with time.

Energy Flux Lost or Carried Away from the System

The temperature of the flue gases oscillated between 1100°C and 1180°C. The energy flux of removed flue gases from the incinerator has fluctuated between 220.6 kW and 1780.8 kW. The average energy flux value was obtained at 1000.70 kWin the testing. The heat flux lost due to heat transfer through the combustion chamber was 22.9kW. Figure 9 shows the physical and chemical enthalpy flux of flue gases exiting the discharge chamber with an increment of time.

Estimation of the Potential of Solid Waste for Electricity Generation

MSW's volume and physio-chemical characteristics are two significant factors in evaluating the capability and power generation. Plastic has the highest calorific value, 35625 kJ kg^{-1}. Paper has a calorific value of 15286 kJ kg^{-1}, followed by wood with 14809 kJ kg^{-1} and textile having 12856 kJ kg^{-1}.

The annual energy consumption of India in 2020 was 31.98 exajoules. A general calculation for the potential of electrical power generation has been calculated based on the Indian population @ 1.38 billion and 53878 billion MT solid waste per year. The gross electricity consumption in FY2020 was 1208 kWh per capita in India.

Charge Rate for Electricity = Rs. 8.50 per kWh (assumed)

The annual cost of electricity per capita = 10268 Rs per capita

The annual cost of electricity for the total population in India = 14169.84 *billion rupee* =188.93 *billion US$*

Total energy requirement in a year = 1667.04 billion kWh

Own consumption = 1,137.00 billion kWh

Quantity of MSW generated daily = 147,613 metric tons

Quantity of MSW generated in a year = 53878745 *metric tons*

Only 50 percent of waste is suitable for power generation,and 500 kWh of electrical energy can be generated from one ton of MSW.

Energy generated from the MSW = 13.46×10^9 kW

Therefore, % Contribution of MSW = 0.8074%

This shows that municipal solid waste has the potential to generate more than 0.8074% of electric energy distributed annually in the municipality.Therefore, the economy saves 0.8074% of 188.93 billion US $=1.5254 billion US $. So, about 1.5254 billion US $ can be saved annually using solid waste as alternative energy in Indian municipalities.

Net power calculation for 100-ton MSW (assumed)

Study I-Analysis the total energy production output (basis on laboratory experiments)

$$LCV = \text{Gross calorific value} - \text{Weight of hydrogen of fuel burnt} \times 9 \times \text{Latent heat of steam} \quad (24)$$

H_2 = % of hydrogen.

Driven Net Calorific Value = 1467.88 kcal/kg

% of Hydrogen = 3.65

Assuming municipal solid waste amount (A) = 100MT

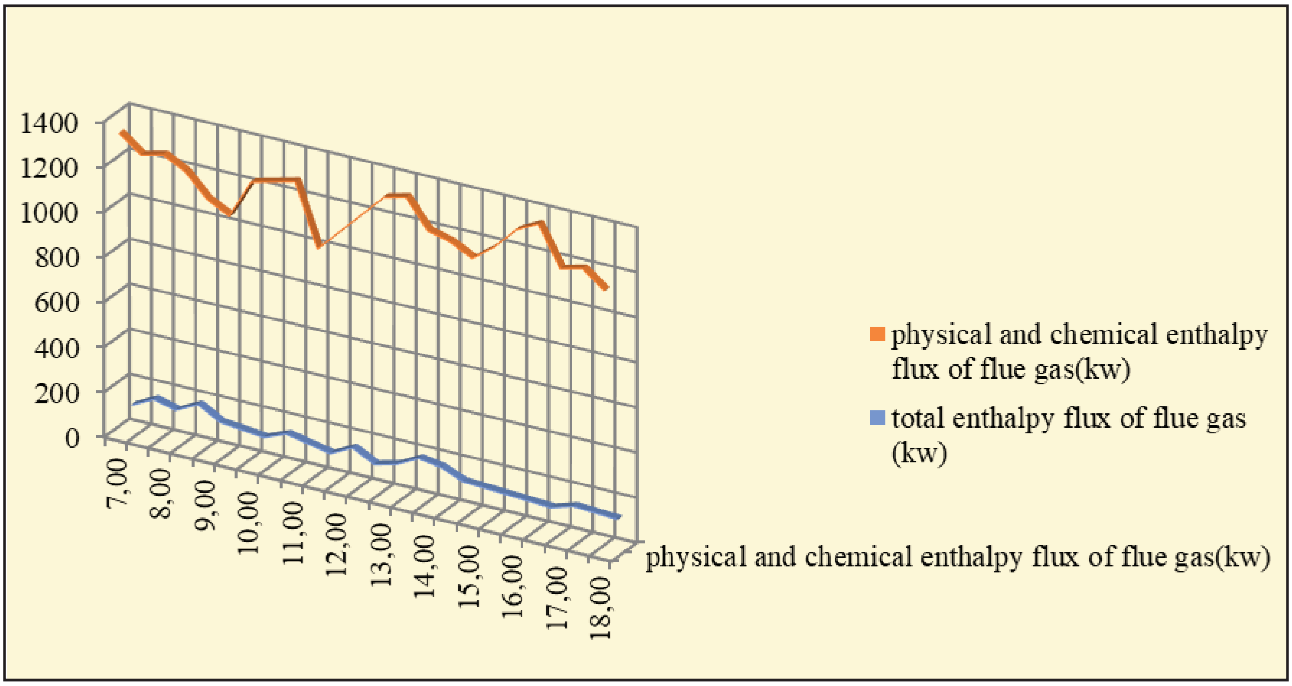

Figure 9. Physical and chemical enthalpy flux of flue gases in the discharge chamber.

GCV (Gross calorific value) = 1467.88 kcal/kg
LCV = 1246.11kcal/kg
Assuming municipal solid waste amount of 100MT as a standard calculation,

$$\text{Energy production capability} = 1.16 \times \text{Net Calorific Value} \times A/24 \quad (25)$$

Study II-analysis the total energy production output (basis on the experiment)

Gross Calorific Value= 1845.80 kcal/kg
Net percentage H2 = 7.7 +3.65 = 11.35%

$$\text{Net Calorific value} = \text{Gross Calorific Value} - 0.09 \times \text{vale of H2} \times 587\ \text{Kcal/Kg} \quad (26)$$

Assuming a municipal solid waste amount of 100 MT,

$$\text{Power production capability} = 1.16 \times \text{Net Calorific Value} \times A \times 100/24 \quad (27)$$

The above shows that about 6MW energy will be produced from 100-ton solid waste, and the above calculation gives the summarized calorific value of solid waste.
i) LCV of Solid Waste = 1246.11kcal/kg
ii) HCV of Solid Waste = 1845.73 kcal/kg

Environmental Benefits of WTE: -In incineration techniques, residual materials are negligible,and no land-filling is required [41]. Energy and environmental factors were included to evaluate different solutions [42]. Extruded energy materials are drawn from the bottom of the grate. These materials contain zero heating value components like glass, iron, etc. By incineration, CO_2 radiation can be minimized to a great extent. Energy generation from waste can reduce CO_2 radiation up to 48567 ton CO_2-eq/year. So, WtE is a good substitute for minimizing CO_2 radiation. Methane gas is produced due to routine dumping of solid waste in dump yards and leads the amount of non-captured methane gas to 0.361 tons of carbon equivalent/ton MSW or 1.34 tons of CO_2/ton of MSW. The calculated value of 1.34 tons of CO_2 for one-ton solid waste is a comparative evaluation in Brazil and less than the estimated 1.52 of CO_2, 17.5 for Australia, and 19.0 for Israel.

Economic Viability

The feasibility and financial parameters of the solid waste incineration system have been determined. The technology is feasible for more than 100 tons of solid waste incineration.The obtained result is viable with economic analysis as stated in other research in developing countries like Argentina, Saudi Arabia, Egypt, etc. Waste to energy plant consists ofinvestment, land, space construction, sale service, testing, and commissioning costs.Indirect costing involves building maintenance, architecture fee, designing fees, and other spare expenses. Table 8 and Figure 14 show that the primary costing for 100 tons of waste to energy plant will be 3.4 million US$, consisting of direct and indirect prices In Appendix 1, the CAPEX cost of waste to energy plant has been calculated is 117.431 billion US$ for 100 tons, and the total investment price of incineration plant is estimated US$ 395.60/kW.

Figure 13 analyses the revenue from disposal and electricity generation.Table-10 shows the revenue from the sale of energy 1660.75MWh/year from100 ton MSW is 15.589 US$ million, and 2.35 US$ million from metal and ash disposal.It is estimated that the net operation price of WtE is equivalent to 2% of Capex value.The total annual cost of electricity production is 15.9-18.8 US$ per 100 kWh.

Table 8. Economic evaluation of WtE incineration plant for 100-ton solid waste

Key parameters	Values	Unit
Plant limit	100	ton/year
Electrical energy	6.44	MW
Thermal capacity	10.5	MW
Internal energy use	2.43	MW
Heat consumption	0.68	MW
Time schedule	8760	hours/year
Shelf Life	20	years
Capex IRR	5.5	%
Increment rate of interest	2.5	%
Actual IRR	2.5	%
Loan reimbursement time	20	year
Income tax	30	%
Sale cost of electrical power	0.216	US$/kWh
Inflation rate of electrical energy	0.2 %	year
Sale coat of heat	0.216	US$/kWh
Gate fee	110	US$/ton

Due to various tribunal laws, the operation and maintenance cost of the incineration system is more than another system. The low calorific value solid waste can be used as a feeder,which is the main factor for WtE technology for various limitations of the financial feasibility of the solid waste plant (100-ton capacity minimum). Gate fees also should be minimized.

CONCLUSION

Solid waste has a heating value of coal equivalent to 9-13 MJ/kg for MSW and 28-32 MJ/kg ofcoal. It can produce about 600kWh of electrical power, as coal produces 3200 kWh. Combined solid waste is burnt in a mass feed incineration system. Incineration technology is installed with high efficiency and combined heat power (CHP) generation capacity. A comparison of various techniques with their various properties has shown in Figure 15. It depicts that incineration is better than any other technology.

WtE plant has many factors affecting the cost analysis space location, waste generation capacity, and mixed solid waste heating value. Economic feasibility also depends on the solid waste condition, flue gas cleaning cost, contaminant waste disbursement price, electricity sale cost, and heat value. One of the significant factors is the extra cost in gate fees applicable on WtE plants. The higher cost of disbursement of ash and waste materials can be affected the net financial features of waste to energy plants.This e-system supports waste-to-energy projects with a range of comprehensive solutions for various operation and process control levels. It effectively optimizes the instrumentation, electrical and control equipment that has been optimized technically and economically,everything from a single source on a profound knowledge of the waste-to-energy processes.

Future Scope of Work

Future work will focus on the plant's best design utilization and feedback.Still, this process has proven itself to have a high capability in fuel feeding systems as a mixed waste of low and high calorific value. The PPP model may be an alternative to install of an incineration plant as a high instrument cost is required for the system.The contemporary world is witnessing the depletion of fossil fuel resources every day, so this is more important to get new energy generation sources and provide more employment to the people by using municipal solid waste, which is available worldwide with hybrid technology application in renewal energy sector.

NOMENCLATURE

MSWI	Municipal solid waste incineration
WtE	Waste to energy
ASTM	American Society for Testing and Materials
MC	Moisture contents
VMC	Volatile moisture content
MJ	Megajoule
KWh	Kilowatt hour
daf	Dry ash free
KW	Kilowatt
GCV	Gross calorific value
NCV	Net calorific value
TWh	Terra watt-hour
MT	Metric tons
LCV	Lower calorific value
HCV	Higher calorific value
NPV	Net Present Values
IRR	Internal Rates of Return
RDF	Refuse Derived Fuel
KPa	kilo Pascal

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

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

ETHICS

There are no ethical issues with the publication of this manuscript.

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Appendix-A

Appendix A1. Detail of primary costing of plant

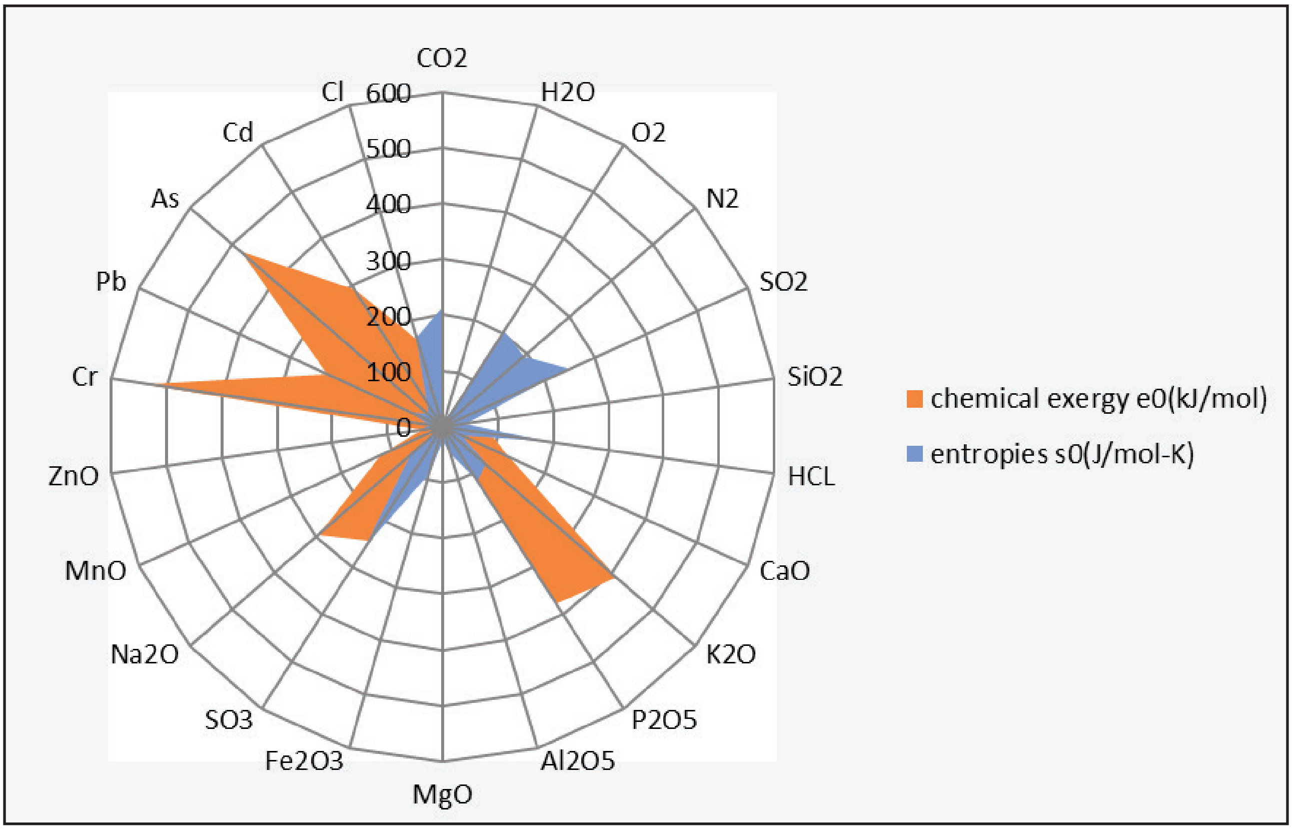
Infrastructure and waste storage	Combustion system and steam generator	Water and steam system	Design	Construction	Electro-mechanical installation	Other cost (Personnel etc)	Total (US$million)
54382.25	17157.21	9942.75	875.4	25189.4	5488.59	4396.33	117431.93

Appendix A2. Revenue from waste disposal and electricity (100 ton MSW and 6.5 MW)

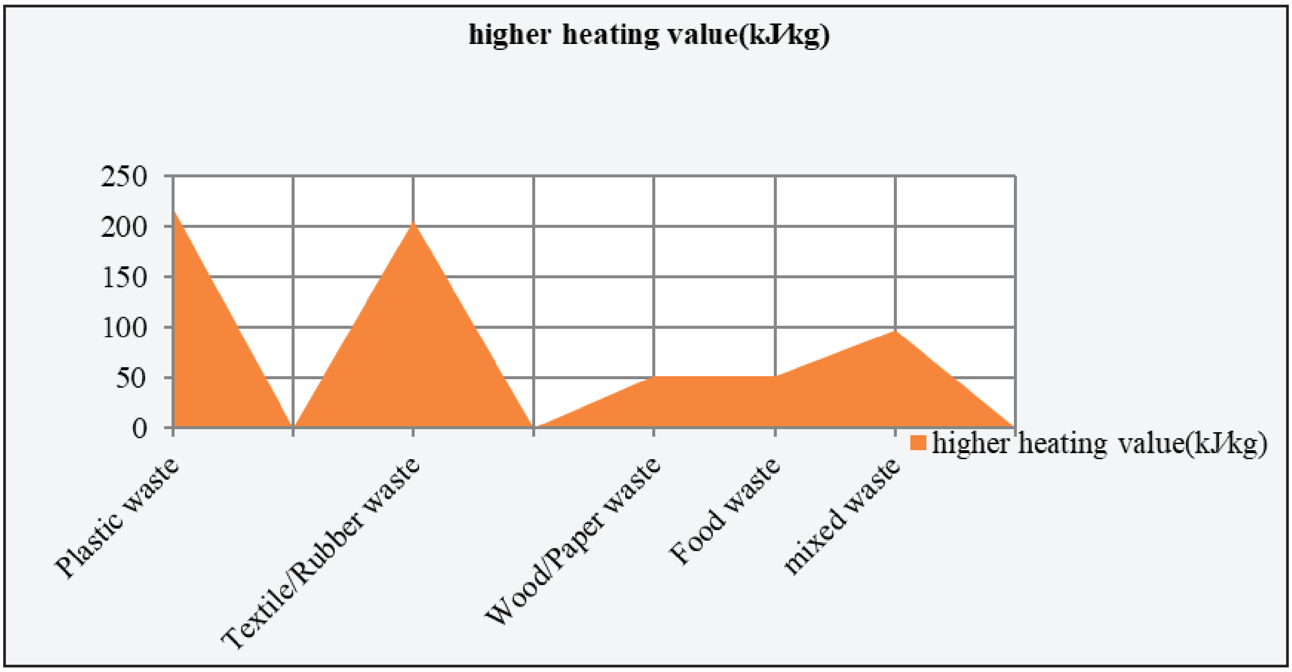
Category	Revenue	Types of power	Sell cost of power/US$/ kWh	Power sell MWh/ year	Earning cost US$ million /year
Revenue from metal disposal	1.97	Electricity	0.216	1660.75	14.116
Revenue from ash disposal	0.38	Heat	0.216	332.15	1.473
Total	2.35	Total revenues from the sale of energy			15.589

All data in US$ million

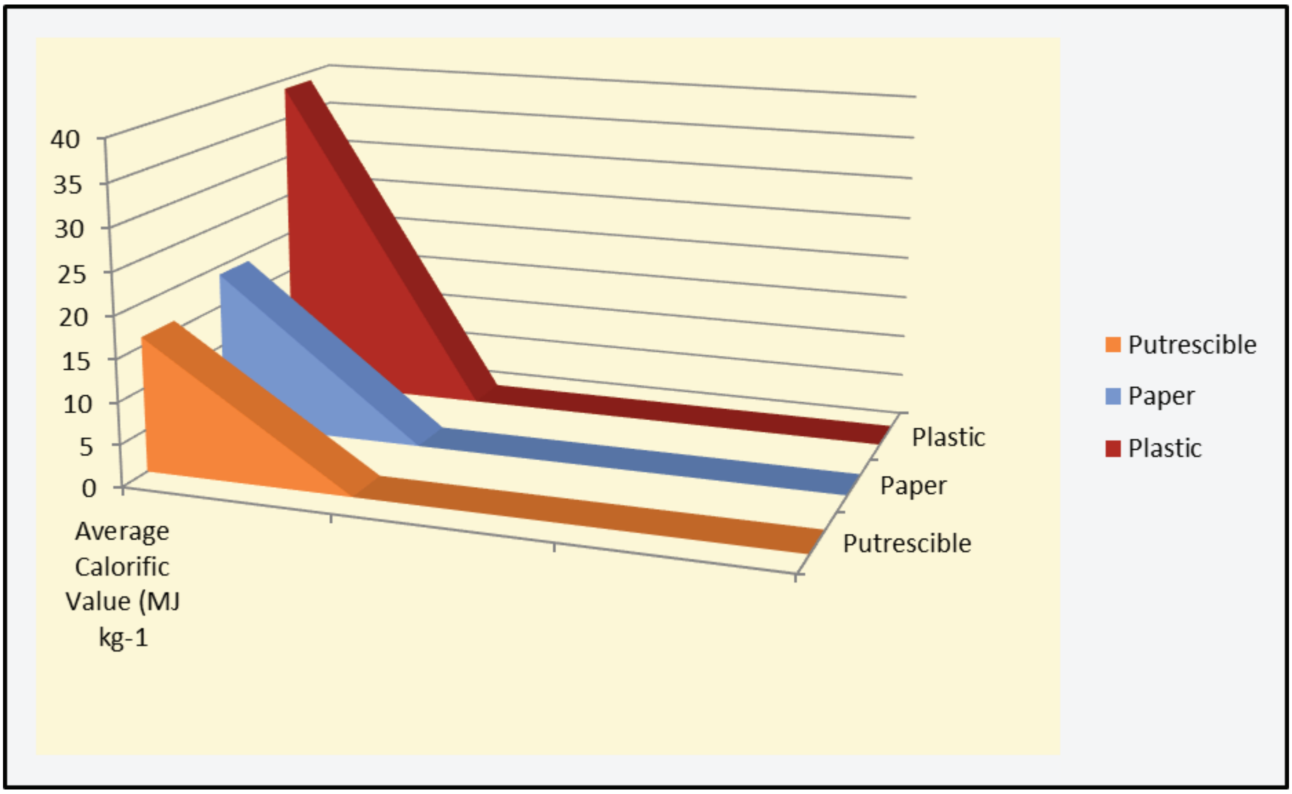
Appendix B



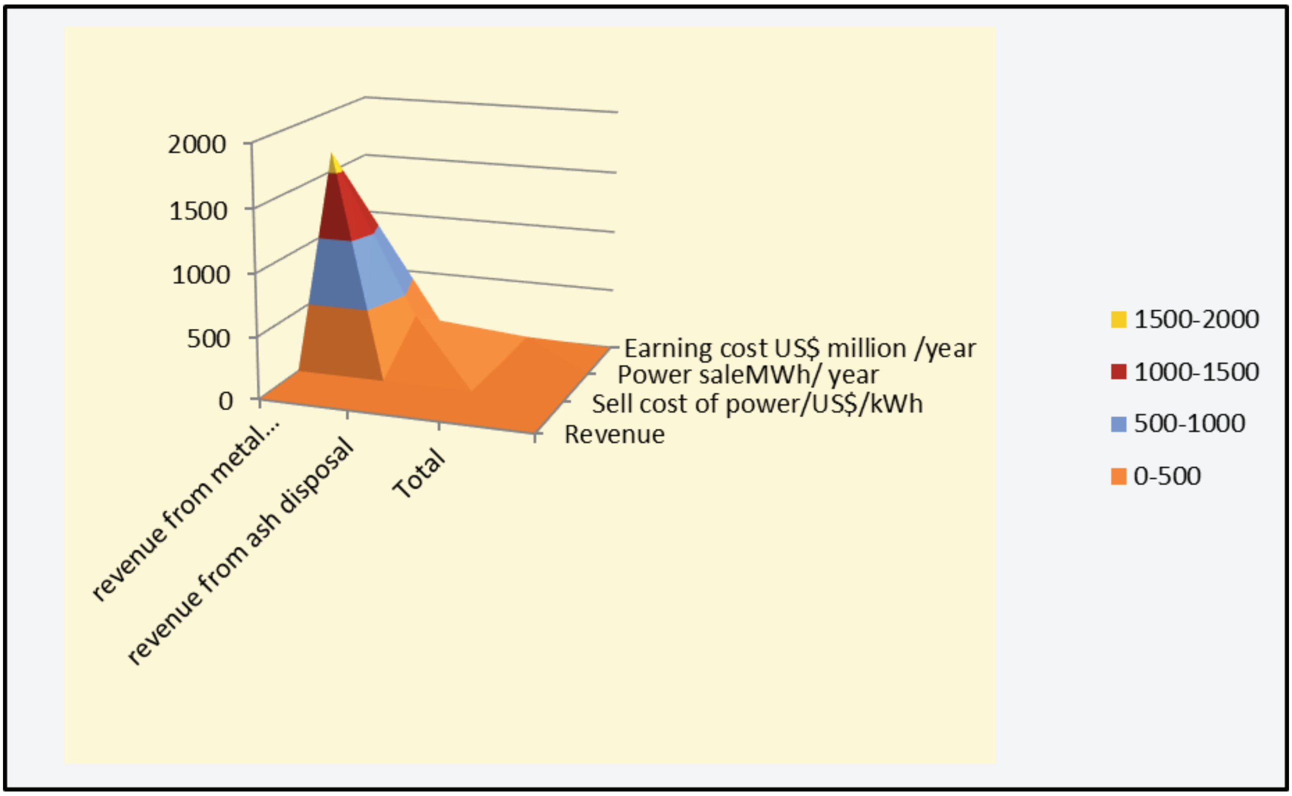
Appendix B1. Comparison of chemical exergy and entropy of different substances



Appendix B2. Comparison of higher heating values of municipal solid wastes.



Appendix B3. Average calorific value of combustible components of solid waste



Appendix B4. Revenue from waste disposal and electricity (100 ton MSW and 6.5 MW)

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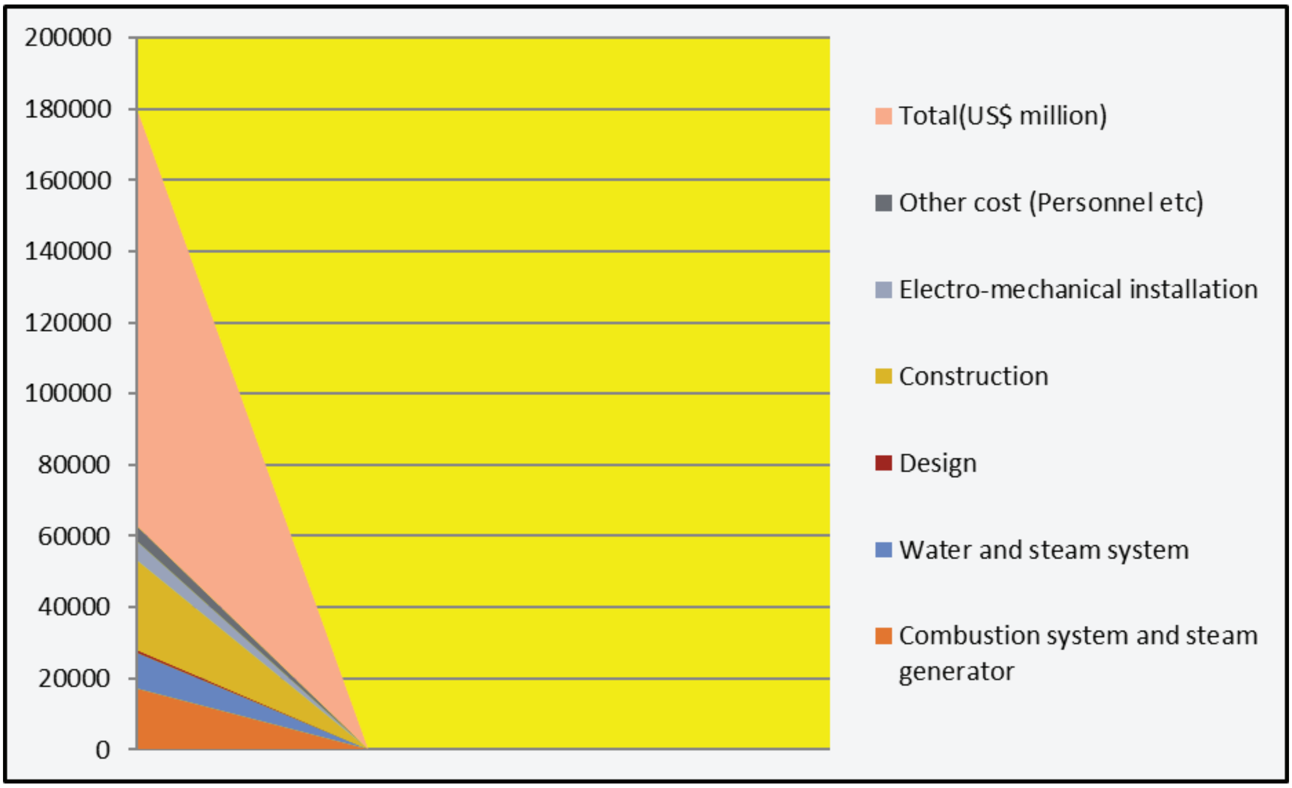
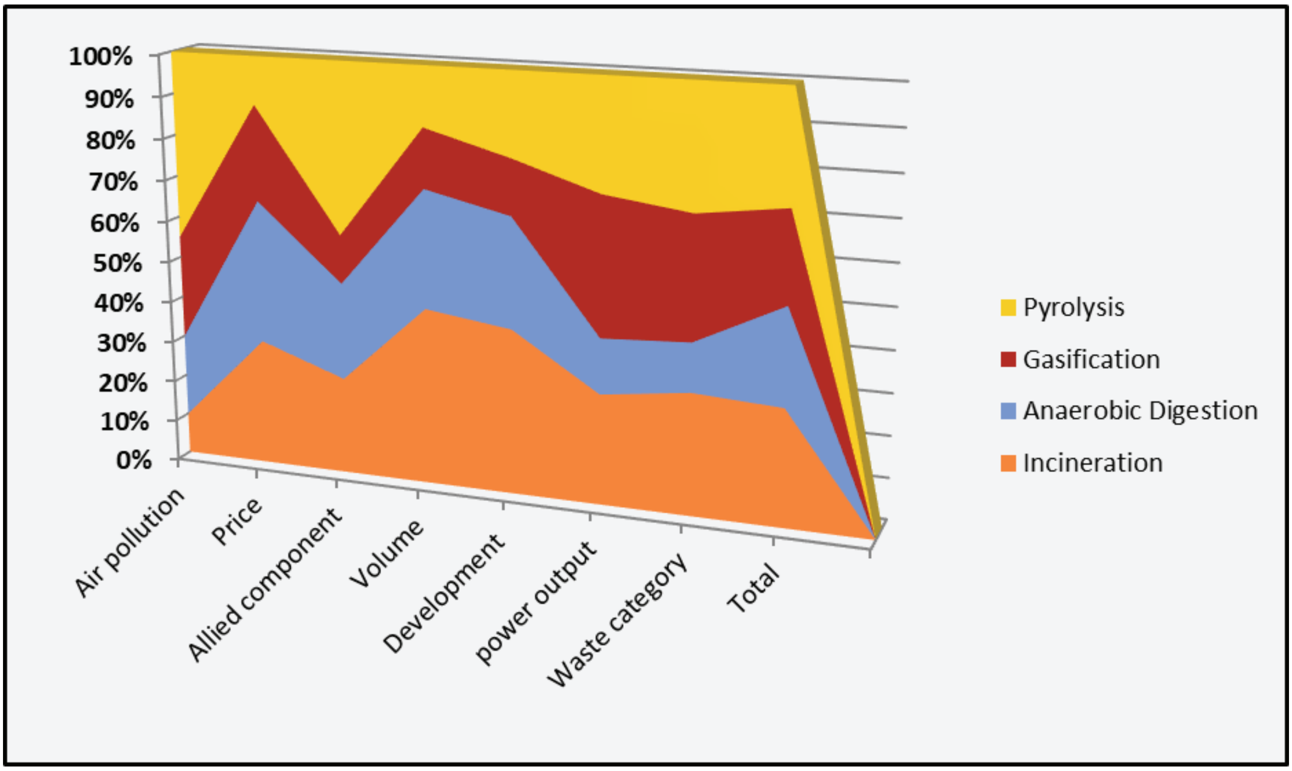


Appendix B5. Detail of primary costing of the incineration plant



Appendix B6. Comparision of various wastes to energy techniques