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Energy Recovery routes from Municipal Solid Waste, A case study of Arusha-Tanzania

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Abstract

A study of energy recovery from municipal solid waste was undertaken. The energy content of the solid waste is 12MJ/kg. The elemental composition shows that the municipal solid waste contains 50% and 5% of carbon and hydrogen respectively. The energy flow (exothermic and endothermic) and thermal degradation analysis were carried out using differential scanning calorimetry and thermo-gravimetric analyser respectively. Experiments were performed at heating rate of 10 K/min, 20 K/min, 30 K/min and 40 K/min in the nitrogen atmosphere at temperature between room temperature and 1273 K. The thermal degradation kinetic parameters values of activation energy (E_a) ranged from 205.9 to 260.6kJ/mol. It has been observed that municipal solid waste is less reactive to combustion as compared to coal and biomass, but its reactivity can be improved through pre-treating process so as to reduce noncombustible materials such as oxygen and ash content. Also pyrolysis and gasification can be used to convert MSW to liquid or gaseous fuel.

Keywords: Municipal Solid Waste, Thermal behavior, Thermo gravimetric Analysis.

1. Introduction

Municipal solid waste generation has been in the increase due to population growth, changing lifestyles, technology development and increased consumption of goods. The increase of wastes generation may lead to environmental problems if not properly managed (A. Johari *et al.*, 2012). Urban centers in developing countries are facing a challenge in solid waste management due to population growth and are constrained by lack of an effective recycling of the biodegradable components into useful materials, poor waste management and waste handling infrastructure (R.K. Henry *et al.*, 2006;J.-H. Kuo *et al.*, 2008).

Despite having abundant solid waste in developing countries, these countries are facing energy crisis which pose a challenge to their economic and social development. Combining waste management with waste energy recovery step from municipal solid waste can address the problems of solid waste management and partly the energy crisis. A disposal method using thermal degradation processing could be a better option for the waste management than biogenic methods. This method has advantages, such as substantial reduction in volume and mass. In order to apply the method in a large scale, there are fundamental parameters such as fuel behavior in thermal degradation, energy contents and its chemical reactions that should be in place so as to assist designers to come up with an appropriate method of waste energy recovery and disposal system (M.J. Quina *et al.*, 2008).

In this study, the thermal degradation behavior of municipal solid waste in a growing urban city of Arusha, Tanzania as a case study is undertaken. This includes determination of its proximate analysis, ultimate analysis higher heating value and kinetics.

2. Material and Methods

2.1 Methodology

The methodology consists of sampling selection, sorting and laboratory analysis to determine the chemical and physical properties of municipal solid waste of Arusha city. The method of sampling was based on ASTM D5231 namely random truck sampling and quatering (A. AbdAlqader and J. Hamad, 2012). In this study the wastes were collected by means of push carts and donkey carts, and were randomly collected from different collecting point of Sakina, Kaloleni and Central market within the Arusha City. The wastes were sorted and weighted by using weighing balance and then separated according to defined classification such as plastics, glass, paper, food waste and metals. The non-combustible wastes were removed from the rest of the wastes. The combustible waste was availed for analysis in accordance to the method developed by (P. McCauley-Bell *et al.*, 1997;G.S. Yang, 2012).

In order accurately to get waste composition an average weight of about 200kg of municipal solid waste was taken. The waste was then taken as good representative of the total municipal solid waste composition at each collecting points under this study. The samples were subjected to standards test methods of proximate and ultimate analysis in accordance to ASTM D3172 and ASTM D3176 respectively.

The thermal degradation analysis was studied under Nitrogen condition using a thermo gravimetric analyzer type

NETZSCH STA 409 PC Luxx connected to power unit 230V, 16A. High purity nitrogen, 99.95% used as carrier gas controlled by gas flow meter was fed into the thermo gravimetric analyzer with flow rate of 60ml/min and a pressure of 0.5 bars. In the STA 409 PC Luxx, proteus software was utilized to acquire, store and analyze the data.

2.2 Sample preparation

The samples were shredded into smaller pieces of approximately 30mm size, mixed and grounded in a grinding machine to less than 1mm size, this is in order to increase surface area of the sample that will allow easier penetration of heat (M.H.M. Yusoff and R. Zakaria, 2012). Then a sample of 30 ± 0.1 mg with average particle size less than 1mm was loaded to crucible and subjected into furnace and heated from 303 to 1273 K at heating rate of 10 K/min, 20 K/min, 30 K/min and 40 K/min. The heating rate variation changes the peak temperature of the decomposition, as the heating rate increases, the peak temperature also increases (S. Ledakowicz and P. Stolarek, 2003). The calculated thermo-gravimetric output from proteus software was obtained as thermal decomposition profile; thermo-gravimetric (TG), differential thermo-gravimetric (DTG) and differential scanning calorimetry (DSC) curves.

Heat release and absorbed by municipal solid waste degradation was determined by using differential scanning calorimetry curves. The DSC monitors heat effect associated with phase changes transitions and chemical reactions as a function of temperature (R. Huffman and W.-P. Pan, 1990). The heat was determined by calculating the area between the baseline and the curve. The heat can be positive or negative. When the heat is positive the process is endothermic and when the heat is negative the process is exothermic (M. Tettamanti *et al.*, 1998).

2.3 The kinetic parameter.

The kinetic parameter was determined by using Kissinger's method. This is used as a standard method for studying the thermal degradation of municipal solid waste under non isothermal condition (S. Ledakowicz and P. Stolarek, 2003). The rate constant is expressed by Arrhenius Equation (1) where, k is the rate constant, which is temperature dependent (T. Sonobe and N. Worasuwannarak, 2008).

$$k = A \exp\left(-\frac{E_a}{RT}\right) \quad (1)$$

$$\frac{dx}{dt} = Af(x) \exp\left(-\frac{E_a}{RT}\right) \quad (2)$$

$$x = (w_0 - w_t) / (w_0 - w_\infty) \quad (3)$$

where, x is the reacted fraction, w_0 the initial mass, w_t the mass remaining at time t , w_∞ the final mass, T the absolute temperature, E_a the activation energy, A the pre-exponential factor, R the universal gas constant and $f(x)$ the algebraic function depending on the reaction mechanism. The temperature rise at a constant heating rate (β) is expressed as shown in Equation 4.

$$\beta = dT/dt \quad (4)$$

Equation 5 is a result of differentiation of Equation 2

$$d^2x/dt^2 = \left\{ \frac{E_a \beta}{RT^2} + Af'(x) \exp\left(-\frac{E_a}{RT}\right) \right\} \frac{dx}{dt} \quad (5)$$

The maximum rate occurs at a temperature T_{peak} ; approximations at T_{peak} condition yield Equation 6.

$$\ln\left(\frac{\beta}{T_{peak}^2}\right) = \ln\left(\frac{AR}{E_a}\right) - \left(\frac{E_a}{RT_{peak}}\right) \quad (6)$$

Equation 6 is a straight line graph, of $\ln(\beta/T_{peak}^2)$ v/s $(1/T_{peak})$, The line slope is E_a/R and the intercept on the vertical axis is $\ln(AR/E_a)$, which are used to determine the values of E_a and A .

The fractional pyrolysis of municipal solid waste component is obtained by taking the ratio of the change mass of municipal solid waste component at time t and total reactive mass of a sample as shown in Equation 3.

3. Results and Discussion

3.1 Proximate and ultimate analysis

The results of proximate and ultimate analysis are shown in Table 1. The moisture content of the municipal solid waste as received ranges between 55.70 and 63.99 wt. %, which is more than 50 wt. % of the total weight of the sample. This high moisture content is prohibitive for combustion process as it rises the ignition temperature, also its contents reduces the calorific value of the fuel (M. Muthuraman *et al.*, 2010), the moisture could be reduced by drying. The volatiles released on dry basis of MSW for Kaloleni, Sakina and Central market are 74.43, 84.00 and 78.31 wt.%, respectively, whilst the volatile matter contained in pure biomass such as forest residue, oak wood, and pine are 79.9, 78.1 and 83.1 wt. % respectively (S.V. Vassilev *et al.*, 2010). Generally, fuels that contains high volatile, have low fixed carbon, the case is same for the municipal solid waste from Kaloleni which has fixed carbon of about 17 wt. %, which is higher than that of Sakina and Central market. The advantage of high volatile and low fixed carbon is rapid burning of a fuel, while a fuel with low volatile and high fixed carbon like coal need to be burn on a grate as it take long time to burn out, unless it is pulverized to a very small size (P. McKendry, 2002) Therefore the value of volatile matter and fixed carbon shows that the municipal solid waste is combustible. The ash range between 3.29 to 5.97 wt. %, which is small, this is advantage to waste management and environment because the possibility of having small quantity of heavy metals, salts, chlorine and organic pollutant is small (C.H. Lam *et al.*, 2010). The ultimate analysis of the municipal solid waste shows that the concentration of phosphorus and chlorine are negligible, the carbon and hydrogen content were above 50% and 5% respectively. The oxygen content was more than 34%. Sulfur is about 0.29%, this is low compared to values from 1.1 wt. % of bituminous coal analysis (T. Nakao *et al.*, 2006).

Table 1: Proximate, ultimate analysis and HHV of Arusha municipal solid waste

Location	Proximate analysis					HHV (MJ/kg)	
	Moisture of received MSW (wt. %)	Volatile (wt.%) dry basis	Ash (wt. %) dry basis	Fixed carbon (wt. %) dry basis			
Kaloleni	59.67	74.43	8.16	17.41		11.90	
Sakina	63.99	84.00	10.00	6.00		11.37	
Central market	55.70	78.30	13.48	8.22		12.76	
Location	Ultimate analysis						
	C (wt. %)	H (wt. %)	O (wt. %)	N (wt. %)	S (wt. %)	Cl (wt. %)	P (wt. %)
Kaloleni	55.57	5.34	34.88	2.09	0.31	0.04	0.10
Sakina	55.70	5.29	34.27	2.13	0.22	0.07	0.13
Central Market	53.20	5.24	34.71	2.86	0.37	0.04	0.11

3.2 Calorific value

The municipal solid waste calorific value is about 12 MJ/kg. This value is smaller than average biomass heating value of about 17MJ/kg (F. Heylighen, 2001) This means energy release during combustion of MSW is smaller compared to biomass combustion. This means that one needs to burn larger amount of MSW to get the same amount of energy. The energy content of MSW can be improved by pre-treating the MSW so as to reduce oxygen amount, since oxygen reduces the energy content of a fuel (P. McKendry, 2002). The MSW can be co-fired with coal for improving energy content (M. Sami *et al.*, 2001; Z. Li *et al.*, 2004). Other processes to improve energy content of MSW are pyrolysis, gasification or torrefaction, these are used to produce bio-oil, syngas or char respectively.

The municipal solid waste from all collecting points degraded to 75 to 85 wt. % in the thermo gravimetric analyser as shown in Figure 1. The MSW from Central market degraded by 85 wt. %, while the Kaloleni degraded by 75 wt. %. The residue formed is between 25 and 15 wt. %. The residue contains fixed carbon and ash, the high residue is observed at MSW from Kaloleni (25 wt. %) and the lowest residue is observed at MSW from Central market and Sakina 15 wt. %. The char can be used as a fuel, but MSWs that have high ash content hinder the combustion of char due to the layer of ash formed on the surface it inhibited the diffusion of oxygen into the char (D.A. Himawanto *et al.*, 2013).

3.3 DTG curves

Figure 2 shows the derivative of thermo-gravimetric analysis (DTG), which has four visible regions; these are moisture release region, lignocellulosic degradation region, plastic degradation region and char pyrolysis region (Z. Lai *et al.*, 2011).

The moisture release region is ranging between 303 and 423. Lignocellulosic degradation region ranges between 423 and 643 K, at these region volatile matters are released; the region corresponds to pyrolysis of lignocellulosic biomass. The plastic degradation ranges between 643 and 913 K and the char pyrolysis region ranges between 913 and 1273. The same identified regions were also observed by Lai *et al.*, (2011).

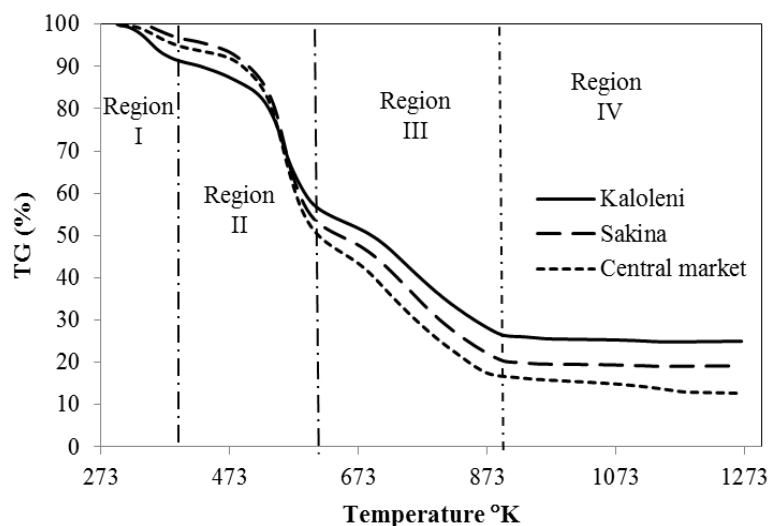


Figure 1: TG of Municipal solid waste

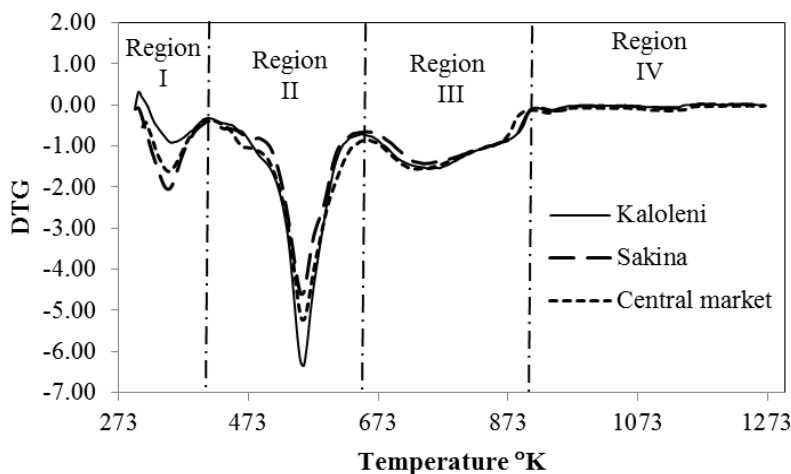


Figure 2: DTG of municipal solid waste

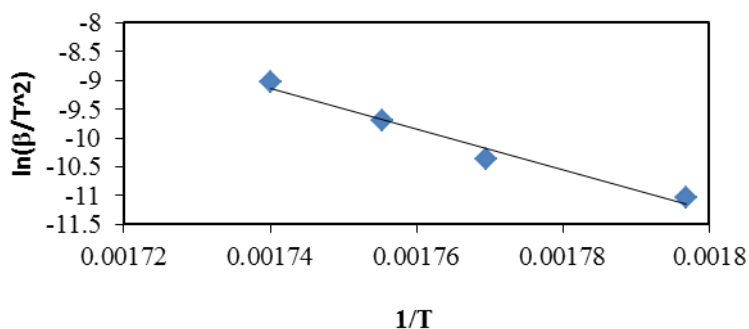


Figure 3: Determination of kinetic parameter of Arusha municipal solid waste.

DTG curves at different heating rate were used to develop Figure 3, which was used to calculate the activation energy (E_a) and pre exponential factor (A), as given in Table 2. The activation energy of MSW ranged between 205.934 kJ/mol and 260.60kJ/mol. This value is higher than that of biomass and coal which range between 50 and 180kJ/mol and 30 and 90 kJ/mol respectively. This corresponds to the biomass of cypress wood chips and macadamia nut shells as observed by Vhathvarothai *et al.* (2013), that the value was 168.7kJ/mol and 164.5kJ/mol respectively (N. Vhathvarothai *et al.*, 2013). This shows that MSW need high energy to react as compared to biomass and coal. The reactivity of MSW can be increased by reducing the noncombustible material such as oxygen and also to remove volatile material, these can be done by pretreating the material through torrefaction process (A.K. Biswas, 2011).

Table 2 Activation energy and Pre-exponential factor of municipal solid waste

Location	E_a (kJ/mol)	A (s^{-1})
Kaloleni	258.680	9.142×10^{23}
Sakina	205.934	8.977×10^{18}
Central Market	260.60	1.186×10^{28}

3.4 DSC curves

The differential scanning calorimetry (DSC) curves shown in Figure 4, reveal endothermicity between 303 and 423, this is due to evaporation of moisture. In the temperature range of 423 to 1273 K the process undergoes exothermic reaction due to the devolatilization of the municipal solid waste and plastic pyrolysis. The energy absorbed due to evaporation of moisture for wastes from Kaloleni, Sakina and Central market collecting points were 0.11 MJ/kg, 0.20 MJ/kg and 0.15 MJ/kg respectively, whilst energy released from the same respective collection points were -7.6MJ/kg, -8.3 MJ/kg and -8.5 MJ/kg in respective manner. The energy released in the DSC by municipal solid waste was lower than higher heating value (12.54 MJ/kg). This is because the DSC used nitrogen as heating media while in bomb calorimeter oxygen is applied for combustion.

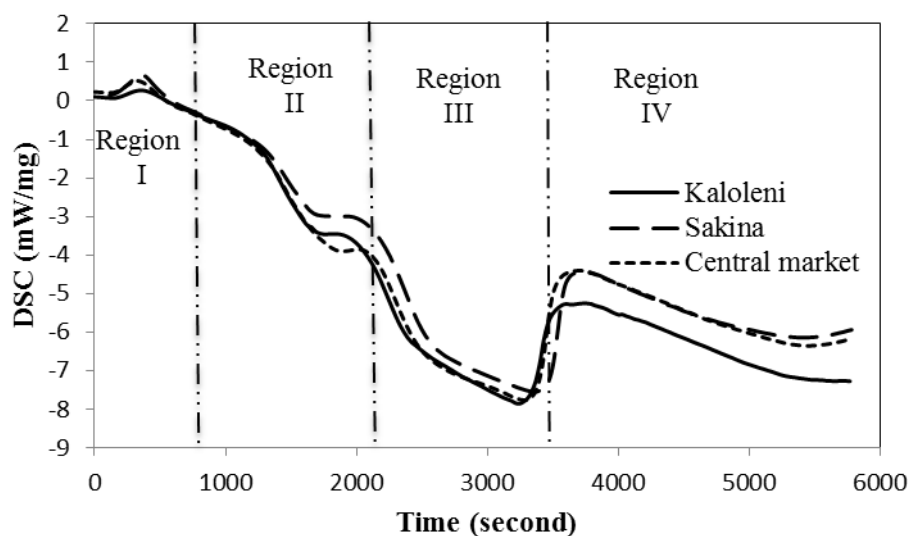


Figure 4: DSC of Arusha Municipal solid waste sites.

4. Conclusion

This paper presents finding related to municipal solid waste characterization of Arusha city. The proximate analysis of municipal solid waste show that, the waste contains more than 50% and 5% of carbon and hydrogen respectively which may contribute to high calorific value of Arusha municipal solid waste. The ultimate analysis shows that average amount of nitrogen, sulfur, chlorine and phosphorus are small, these reduce emissions during combustion.

The energy content of waste determined by bomb calorimeter is about 12MJ/kg this is about 30% of energy containing in coal and 60% of energy containing in biomass. The activation energy was ranging between 205.9 and 260.6kJ/mol. The municipal solid waste shows exothermicity property at the devolatilization zone. The

devolatilization zone shows that the municipal solid waste can be easily ignited at temperature above 423 K. Therefore municipal solid waste has a good potential to be used as a fuel.

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6. List of Abbreviation

ASTM	American Standard Test and Methods
COSTECH	Commission for Science and Technology
DSC	Differential scanning calorimetry
DTG	Differential thermal gravimetric
HHV	Higher heating values
NM AIST	Nelson Mandela African Institute of Science and Technology
TG	Thermal gravimetric analysis
UDSM	University of Dar es Salaam

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