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Characterization of Municipal solid waste for energy recovery.
A case study of Arusha, Tanzania.

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Abstract- The characterization of municipal solid waste is important in designing waste management, and waste to energy systems. This work characterizes the municipal solid waste of Arusha city; the results show that the HHV of municipal solid waste is about 12.42 MJ/kg. Thermo-degradation analysis shows that the municipal solid waste has activation energy ranges between 60 and 70 KJ/mole and pre-exponential factor ranges between 1.07 x 10^3 to 9.29 x 10^5 (S^{-1}).

Keywords— characterization, municipal solid waste, energy, incineration

I. Introduction

Municipal solid wastes are generated to any society due to daily human activities. The waste generation of municipal solid waste has increase radically, due to population growth, changing life styles, technology development [1] and consumption of goods with packaging materials which are non-recyclable. The increase of wastes may give serious environmental problems if not properly managed.[2]. Currently various methods used in waste disposal are recycling, composting, landfilling, open dumping and thermal disposal [3, 4].

Recycling is cheap and is easily done, it save a lot of energy, money, resources and thereby reduce pollution. Municipal solid waste can recycle papers, glass, aluminum and plastics [5, 6].

Due to the increasing cost of raw materials, recycling provides a cheaper source of raw materials for industries and serve energy [7]. Composting is a natural process involves the decomposition of free from hazardous biodegradable waste materials through microorganisms into organic compounds that can be used as fertilizer [8]. However, if the waste contains a big fraction of plastic, which are non-decomposable, thermal decomposition is better method for disposal [9].

Landfill is the deposition of waste into land; landfill has been the most common method of waste disposal for many years [10].

Landfill involves the use of a large area. The area is then covered up with soil. Landfills give off gases like methane, which can be dangerous [11]. The lack of landfill sites and environment consequences caused by landfill makes most countries to ban the landfill of combustible waste [12]. Open dump is common methods of waste disposal in most developing cities [13]. Open dump makes possibilities for highly environmental pollution because dumps were selected based on convenience instead of the environmental safety consideration [7, 14].

The possibility of taping biogas produced by the anaerobic digestion of organic waste is the feasible alternative to minimize the negative effect of landfill and open dump to the environment. The tapped gas can be processed and commercially utilized [15].

Incineration, gasification and pyrolysis are common method of thermal waste disposal. Incineration is the method which leads to a great reduction in quantity of waste up to 80% in mass and 90% in volume [10].

The method's ability to reduce municipal solid waste mass and volume, its environmental impact associated with waste disposal and it's positively to energy production, makes it acceptable as effective method of waste disposal [16, 17]. There is a misinterpretation of incineration in general; the incineration seems to be a big pollutant to the environment. This is not true for well-designed incinerators which take into consideration the elimination of these pollutions [18]. Incineration with energy recovery will enable us to utilize the dormant energy source present in the waste to electricity and heat [19]. Incineration reduces the amount of waste to dump, improve recycling and minimize the dependence on fossils fuels as the only source of energy [20]. Gasification is the process in which the municipal solid waste polymers are decomposed by heat to simple gases such as CH_4, CO and H_2, which are collected and use as a source of energy. These gases can be used directly in heating and in the internal combustion engines [15].

At present in Arusha, the only disposal technique used is open dumpsite. The method is lack of good and appropriate environmental pollution control. The problem of transportation of waste to the dumpsite which is located at Murriet area in Sokoni one ward, about 8 kilometers from city center is a big challenge to city. Incineration of municipal solid waste with energy recovery is more option than other methods, this is because the incineration generate sterile and no hazardous end product. Switching to incineration may also minimize the possibility of risk of contaminants to dumps [21].

Municipal solid waste is composed by different types of waste fractions and each has its own combustibility and energy contents [22]. That is why the design of an incinerator is the most complex [23].

In this study, the characterization of municipal solid waste a case of Arusha, Tanzania is undertaken. This includes proximate analysis, ultimate analysis, in order to determine the elemental components of sample for understanding the reactions products. It will help in determine theoretical air-fuel ratio in thermo conversion systems, calculating heating values and provide information on the pollution potential of the municipal solid waste. Thermo gravimetric (TG) and differential thermo gravimetric (DTG) in order to understand the pyrolysis degradation behavior of municipal solid waste. This work will assist in collect data and information for guiding in modeling, design and operation of incinerator with minimum effluences [20, 24].

II. MATERIAL AND METHODS

A. *Material*

Municipal solid wastes from Arusha city were used in this study. The wastes were collected from different collecting centers within the city. These collecting centers were Kaloleni, Central market, Sakina and Tengeru.

Waste were sorted to remove non-combustible materials, the remaining wastes were reduced to about 200 kgs by coning and then quartering to small amount The samples were packed and sealed in polythene bags of about 2kgs and put in an air tight container which contains 3 bags from every collecting point. The total of four airtight containers was taken to laboratory for analysis. Standards test methods were adopted for establishing the laboratory analysis. Three experiment tests were carried out from each waste sample.

B. *Proximate analysis study*

The proximate analysis is done in order to estimate the heating value of municipal solid waste fuel. It is done to determine the composition of municipal solid waste in terms of gross components of moisture, volatile matter, fixed carbon and ash.

a) *Moisture*

The moisture content was determined according to ASTM E1756-01 standard. One gram of municipal solid waste was placed into an oven at 105℃ for two hours. The sample was then cooled in desiccator and reweighed. The difference in weight represents the moisture content of the sample expressed in percentage.

b) *Volatile matter*

Volatile matter of a municipal solid waste fuel is vapor released when the fuel is heated. The applicable ASTM standard E-872 [25] for determination of volatile matter was used. The previous sample used for moisture determination, was again heated in a covered crucible to avoid contact with air during devolatilization. The covered crucible was placed into a furnace at 950℃ for two hour. Then the crucible was taken out, cooled in desiccator. The weight difference due to devolatilization was referred as volatile matter.

c) *Ash*

Ash is the inorganic solid residue left after the fuel is completely burned. The procedure used to determine ash was using ASTM D1102 [25]. The remaining sample from volatile matter calculation was placed in the furnace at 575 ℃ for an hour for combustion. All carbon was burnt, and sample was cooled and reweight.

d) *Fixed carbon*

Fixed carbon in fuel was determined by the difference from the moisture, volatile matter and ash contents.

FC= 100 - M - VM - ASH

Where: *FC* - Fixed carbon, *M* - Moisture, *VM* - Volatile matter and *ASH* – remaining ash

Fixed carbon represents the solid carbon in the MSW that remains in the char after devolatilization process.

C. *Calorific value study*

The calorific value represents the amount of chemical energy in a given waste components, which depends on its carbon, moisture and hydrogen contents of the waste [19]. The calorific value of the sample was determined using standard bomb calorimeter type Wagtech Gallenkamp Auto bomb. The municipal solid waste samples were dried and grinded to small particles. The particles were sieved and compress to form pallets. The bomb was assembled and filled with pressurized oxygen about 30bars. The firing circuit was tested and the calorimeter was adjusted by weighing sufficient water into the calorimeter vessel to submerge the bomb completely. The bomb was fired and after the temperature stabilization the differences were noted and recorded. The calorific values of the municipal solid waste were calculated according to ASTM D240 [26].

$$\mathrm{HHV} = \frac{\Delta \mathrm{T C_P}}{\mathrm{m_g}} \quad (1)$$

Where

ΔT, C_p and m_g are change in temperature in K, heat capacity in MJ/kg and mass of sample in Kg

D. *Ultimate analysis study*

The ultimate analysis studies the elemental composition were determined by the deploying of AAS, EPA, BS and ASTM. The cations were determined by drying the sample at 105℃ for 3 hours, cooled in the desiccators, and then grounded to powder form by using pestle and mortal. The samples weighed were recorded. The sample was digested using aqua regia solution. After cooling down the paste, the whole paste in the beaker was added 20mls of de-ionized water, swirling and by using the glass rod the paste were mixed and filtered through the funnel with filter paper into the 100ml volumetric flask. Another portion of 20mls was added to the paste in the beaker, mixed with aid of glass rod and passed through the filter on the funnel. The process was repeated until the volumetric flask was attained. The resulting sample was aspirated in the atomic absorption Spectrometry machine mode AA240. The machine reads three times and displays the average as read out. Element of Zinc (Zn), Lead (Pb), Chromium (Cr), Cadmium (Cd), Iron (Fe), Copper (Cu), Sodium (Na), Potassium (K) and Manganese (Mn) were analyzed using EPA 5050.

E. Thermo degradation analysis (TG)

Thermal degradation characteristics of samples are studied under Nitrogen condition using a simultaneous thermal gravimetric analyzer type NETZSCH STA 409 PC Luxx connected to power unit 230V, 16A. High purity nitrogen, 99.95% was used as carrier gas controlled by gas flow meter is fed to the thermo gravimetric analyzer with flow rate of 60ml/min with a pressure of 0.5 bars. A water bath is connected to the STA 409 to circulate cooling water. In the STA 409 PC Luxx, proteus software is utilized to acquire store and analyze the data in desktop computer. A sample of 30$\pm$0.1 mg with average particle size about 1mm was loaded to crucible and subjected into furnace and heated from 35 to 1000℃ at heating rate of 10 K per min. The calculated thermo-gravimetric output from proteus software was obtained as thermal decomposition profile; thermo-gravimetric (TG) and differential thermo-gravimetric (DTG) curves. The operation of TG is such that the two crucibles were used, the empty crucible and a crucible with sample. The sample is weighted using accurately analytical balance. Both crucibles empty crucible and crucible with sampled are put into the furnace and heated at a constant heating rate of 10 ℃/min. The crucibles are placed on the heat flux sensor. The difference in the heat flow between the sample crucible and empty reference crucible is the measured signal used to determine the material property.

F. Pyrolysis kinetic

The kinetic equation used for calculating isothermal conditions based on first order Kinetic equation.

Municipal solid waste → Solid residue + volatiles

In the present study, non-isothermal analysis method used was Coats and Redfen methods [27].

$$\frac{d\alpha}{d\tau} = k(T)f(\alpha) \quad (2)$$

Where $f(\alpha)$ = is the function which depends on the reaction mechanism,

$$f(\alpha) = (1-\alpha) \quad (3)$$

$k(T)$ The temperature dependent of rate constant

T Is the absolute temperature, τ the time and α the degree of transformation

The temperature dependence of the rate constant is described by Arrhenius equation:

$$k(T) = A\exp\left(-\frac{E}{RT}\right) \quad (4)$$

Therefore

$$\frac{d\alpha}{d\tau} = A\exp\left(-\frac{E}{RT}\right)(1-\alpha) \quad (5)$$

Where A is the pre-exponential factor, E the activation Energy, R the universal gas constant (8.314 mol^{-1} K^{-1}) and α is pyrolysis conversion which calculated as

$$\alpha = \frac{w_o - w}{w_o - w_f} \quad (6)$$

Where w_o, w and w_f are initial mass, mass remaining at time t and final mass respectively.

If β is a constant heating rate ($10℃/\mathrm{min}$) is defined as

$$\beta = \frac{dT}{d\tau} \quad (7)$$

Rearranging equation (5) gives

$$\frac{d\alpha}{dT} = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right)(1-\alpha) \quad (8)$$

$$\frac{d\alpha}{(1-\alpha)} = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right)dT \quad (9)$$

Integrating equation (9), the following equation results will be obtained

$$-\ln(1-\alpha) = \frac{A}{\beta}\int\exp\left(-\frac{E}{RT}dT\right) \quad (10)$$

The integral $\int\exp\left(-\frac{E}{RT}dT\right)$ has no exactly solution; it can be expressed as asymptotic series and integrated, with higher order terms ignored, and the equation (10) becomes

$$-\ln(1-\alpha) = \frac{ART^2}{\beta E}\left[1-\frac{2RT}{E}\right]\exp\left(-\frac{E}{RT}\right) \quad (11)$$

Rearranging equation (11) will give the following equation

$$-\frac{\ln(1-\alpha)}{T^2} = \frac{AR}{\beta E}\left[1-\frac{2RT}{E}\right]\exp\left(-\frac{E}{RT}\right) \quad (12)$$

When express equation (12) into logarithmic form gives equation equivalent to the "COATS and REDFERN method":

$$ln\left[-\frac{ln(1-\alpha)}{T^2}\right] = ln\frac{AR}{\beta E}\left[1-\frac{2RT}{E}\right] - \frac{E}{RT} \quad (13)$$

Assume the value of $\frac{2RT}{E} \ll 1$, we have,

$$ln\left[-\frac{ln(1-\alpha)}{T^2}\right] = ln\left[\frac{AR}{\beta E}\right] - \frac{E}{RT} \quad (14)$$

By make a plot the relationship between

$$\ln\left[-\frac{\ln(1-\alpha)}{T^2}\right] \text{ against } \frac{1}{T}$$

This will give a straight line with slope $\frac{E}{R}$

The activation energy can be calculated from the slope of plotted equation and pre exponential factor can be determined by the value of intercept and known activation energy [28].

III. RESULTS AND DISCUSSION

A. *Waste composition analysis*

The waste composition analysis shows that the municipal solid waste of Arusha composed of 13 % noncombustible waste and 87% of combustible waste. The composition of combustible materials was 3% textiles, 9% Papers, 7% Plastics and 81% Food and organic waste as shown in Figure 1.

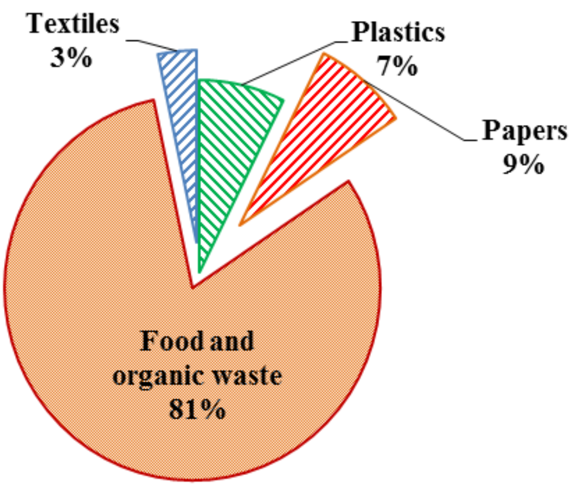

Figure 1: The composition of combustible municipal solid waste

Table 1: Waste composition from various countries

Waste category/ Location	Plastic	Paper	Food waste	Textiles Leather	
Arusha city	7	9	81	3	Original research
Kenya (Nairobi)	15.10	12.36	64	8.54	[22]
Malaysia	12.58	6.72	78.57	2.13	[29]
Uganda	4.87	1.71	92.81	0.60	[1]

B. *Proximate analysis results*

The proximate analysis results are shown in Table 2.

Table 2: Proximate analysis of municipal solid waste

	Proximate analysis			
Location	**Moisture (wt. %)**	**Volatile (wt. %)**	**Ash (wt. %)**	**Fixed carbon (wt. %)**
Kaloleni	59.67	30.02	3.29	7.02
Central market	55.70	34.69	5.97	3.64
Sakina	62.85	32.01	3.42	1.72
Tengeru	64.03	30.77	3.19	2.01
Average	**60.56**	**31.87**	**3.97**	**3.60**

The moisture content of the municipal solid waste ranges between 55.7 and 64.03 wt. %, which is more than 50 wt. % of the total weight of the sample. The volatile matter composition ranges between 30.02 and 34.69 wt. %. Ash ranges between 3.19 to 5.97 wt. % and the fixed carbon ranges between 2.01 to 7.02 wt. %.

The Sakina and Tengeru wastes seem to have same properties with exception of volatile matter. The Sakina waste has 32.01 wt. % volatile matters, while Tengeru has 30.77 wt. % volatile matters. Although municipal solid has high moisture content, it can be dried and used as fuel. If the proximate analysis is based on dry bases, the volatile matter and fixed carbon would be higher.

C. *Calorific value analysis*

The raw data of the experiment were tabulated hereunder table 3

At known average mass of waste fuel burned in stainless steel crucible at constant volume, the average change in temperature in K. The heating value calculated using equation hereunder using a corresponding heat capacity to be 10.822 KJ/℃ can be calculated and results are attached in Table 3

Table 3: Bomb calorimeter results of Municipal solid waste of various parts of Arusha city council.

	Kaloleni	Central Market	Sakina	Tengeru
Crucible + MSW pellet (g)	8.58	8.67	8.66	8.64
mass of crucible (g)	7.72	7.71	7.70	7.70
Mass of MSW Pellet (g)	0.86	0.96	0.96	0.95
Final Temperature in K	36.51	36.14	36.18	36.03
Initial Temperature in K	35.5	35.00	35.12	34.95
Uncorrected temperature rise (K)	1	1.14	1.06	1.08
HHV (MJ/kg)	**12.58**	**12.85**	**11.95**	**12.30**

The average higher heating value of municipal solid waste is about 12.42 MJ/kg.

The calorific value was about 12.42 MJ/kg this value correlates with the value obtained by Eyinda and Aganda from Kenya who estimated the calorific value for Nairobi at about 12.48 MJ/kg [22]. Compared to other fuels such as coal which gives about 37 - 40 MJ/kg and biomass 18 – 20 MJ/kg [30], this means that the energy that can be produced by one kilogram of coal, it can be produced by three kilograms of municipal solid waste. The value obtained from UK shows that the municipal solid waste has the calorific value of 11MJ/Kg [24].

The heating value of municipal solid waste is low and therefore the power production per unit mass is low. But the waste utilization as source of renewable energy is considered as free source and therefore there is advantage of using waste as source of energy [22]

D. Ultimate analysis results

The results of ultimate analysis for determination chemical properties are shown in table

Table 4: Ultimate analysis of municipal solid waste

Location	Ultimate analysis						
	C (wt. %)	H (wt. %)	O (wt. %)	N (wt. %)	S (wt. %)	Cl (wt. %)	P (wt. %)
Kaloleni	55.57	5.34	34.88	4.09	0.31	0.04	0.10
Central Market	53.20	5.24	34.71	2.86	0.37	0.04	0.11
Sakina	55.74	5.36	35.06	1.87	0.31	0.12	0.16
Tengeru	55.92	5.34	34.81	1.846	0.24	0.09	0.21
Average	**55.23**	**5.31**	**34.75**	**2.559**	**0.29**	**0.07**	**0.14**

Table 4, shows the ultimate analysis of municipal solid waste. The carbon and hydrogen content of municipal solid waste are more than 50% and 5% respectively, which contributes to increase calorific value of waste. But the high oxygen content of more than 34% reduces the calorific value. Based on ultimate, calorific value and proximate analysis, the municipal solid waste can support burning. In addition to that the incineration can reduce the volume of municipal solid waste more than 90%, this can be seen in Table 2, where the ash was about 3.97 % of the total weight of the municipal solid waste, this shows that incineration can be a good alternative to manage municipal solid waste.

E. Thermo-degradation analysis results

a) TG analysis

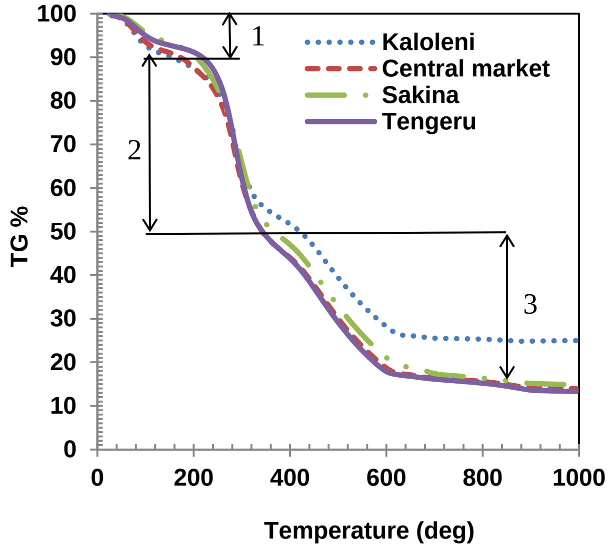

Figure 2: Thermo-gravimetric analysis of Municipal solid waste

Thermo-degradation analysis of municipal solid waste has three parts. The first part is mainly evaporation of moisture and highly volatile materials, the second part is the degradation of lignocellulose biomass and third part is plastic degradation and hemicellulose degradation, as shown in Figure 2. In this analysis the amount in percentage of all material comprises in municipal solid waste were analyzed. Moisture and high volatile materials is about 10%, lignocellulose materials ranges between 35 and 40%. The plastic materials are ranging from 25 to 30%. The residue is ranging from 20 to 25%.

b) DTG analysis

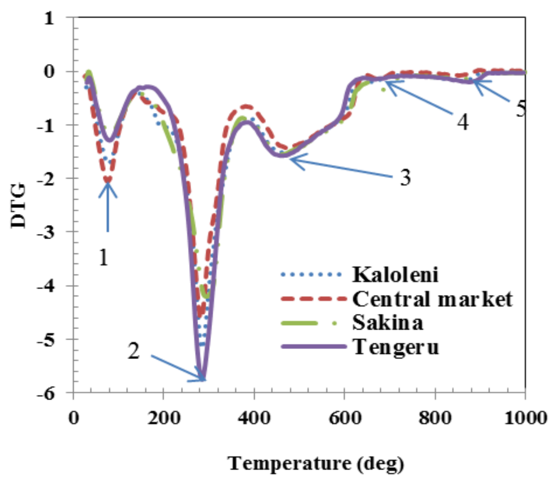

Figure 3: DTG of municipal solid waste

Figure 3 shows the derivative of thermo-gravimetric analysis (DTG); here the degradation of municipal solid waste is shown by peaks. Peaks are corresponding to sections shown in Figure 2. 1st peak is ranging between 30 and 170℃ in this peak moisture and highly volatile materials are removed. The first peak appears at very low temperature due to high volatile materials such as methanol and ethanol which are derived from fruits and vegetables fermentation. 2^{nd} peak is ranging between 170 and 280℃, at this range volatile matters are released, this corresponding to pyrolysis of lignocellulos biomass, lignocellulose biomasses are comprises of hemicellulose which decompose in a range of 160 and 240℃ cellulose which decomposes at range of 240 – 360℃, and lignin which decompose at wider range as shown between 160 – 627℃ [31]. The 3^{rd} peak is plastic degradation it ranges between 280 and 640℃; this region is coinciding with hemicellulose region. The 4^{th} peak is char pyrolysis and it mainly produces syngas. The 5^{th} peak is ash pyrolysis [32].

c) Differential scanning calorimetry

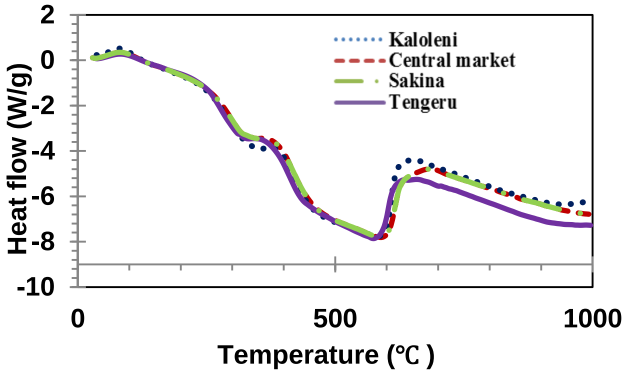

Figure 4: DSC curves of Municipal solid waste

In differential scanning calorimetry (DSC) experiment results curves Figure 4 shows that the endothermic reaction occurs between 105 and 110℃ this is due to evaporation of moisture. From 110 to 1000 ℃ the experiment shows that the process undergoes exothermic reaction. From 110 to 280℃ the energy release is gradually increased as the temperature rise, this is due to degradation of hemicellulose. The temperature ranges between 280 and 300 ℃ the energy released become slightly constant, then from 300 to 580℃ again the release energy is gradually increased, this is due to energy released from cellulose and plastic materials. Between 580 and 640 ℃ the released energy decreases. The released energy again gradually an increase from 640℃ is caused by char pyrolysis.

d) Pyrolysis kinetic

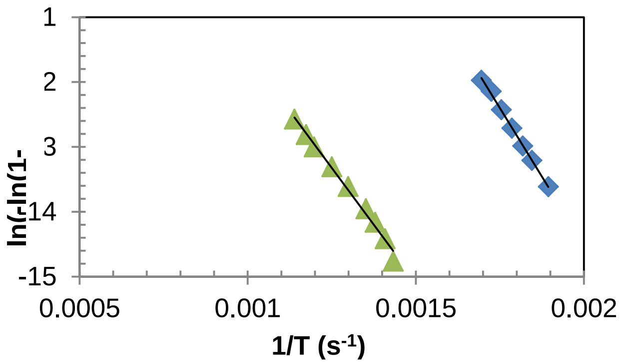

Figure 5: Determination of Kinetic parameters of Municipal solid waste of Arusha

The TG curves at different temperature and mass change Figure 5 were used to calculate the activation energy (E_a) and pre exponential factor of municipal solid waste, the values as given in Table 5 the activation energy (E_a) of municipal solid waste ranges between 60.58 and 70.31kJ/mole while the value of pre-exponential factor ranges between $1.07\,x\,10^3$ and $9.29\,x\,10^5(s^{-1})$. This value of activation energy is within the value of activation energy of biomass which is ranging between 50 and 180 kJ/mole [33]. This value tells us that the temperature range where we calculate the activation energy were the decomposition of biomass fraction of municipal solid waste

Table 5: Activation energy and pre-exponential factor of municipal solid waste

Temp interval (K)	528 – 590	698 – 878
Order (n)	1	1
E_{act} (kJ/mole)	70.30	60.58
A	$9.29\,x\,10^5$	$1.07\,x\,10^3$

IV. Conclusion and Recommendations

- The waste composition shows that there is possibility of utilizing municipal solid waste for energy recovery
- The energy content in municipal solid waste is about 12.42 MJ/kg this is about 69.4% of energy from pure biomass and about 31.3% of the energy of bituminous coal.
- The incineration of municipal solid waste reduces the volume of waste and the net CO_2 emission; it is therefore a better option for solid waste management and the global warming reduction.
- Since the research found that there is potential of utilizing municipal solid waste as source of energy, it is recommended for prototype incinerator to be designed and optimized for energy recovery.
- There is need to educate people in sorting of waste so as to get waste separation right from the source.

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