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Flue Gas Emissions and Performance Evaluation of Small-scale Solid Waste Incinerators at Njokerio and Ng'ondu in Njoro, Kenya

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Authors' contributions

This work was carried out in collaboration among all authors. Author NSGM has come-up with this research, taken the data, performed the statistical analysis, wrote the protocol and the Thesis with supervision of the three authors. All authors read and approved the final manuscript.

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ABSTRACT

Solid waste management is challenging and incineration technique is more preferred to other methods in reduction of mass and volume, removal of odour and energy recovery in both industrial and residential environments. The challenges facing residents at Njokerio, Ng'ondu and Green Valley estates in Njoro, Kenya included poorly designed open-wastes collection systems, exceeding incinerator loading rates and inappropriate operating temperatures. It also include inadequate design specifications, poorly mixed solid wastes with high moisture contents resulting to high emissions of noxious heavy dense smoke. The aim of this study was to evaluate factors influencing flue gas emissions and performance of small-scale incinerators. Data collected were statistically analysed to determine trends, means, *F*-values and Least Significant Different (*LSD*) at $\alpha = 0.05$. Wastes incineration at varying moisture contents (*MC*) from 15 to 75% produced mean emission values for carbon monoxide (*CO*), carbon dioxide (CO_2), and hydrocarbon (*HC*) ranging

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between 5 and 11 ppm, 5 and 14%, and from 508 to 1168 ppm, respectively. Varying the incinerator loading rates from 15 to 75 kg/h yielded means *CO* ranging between 5 and 12 ppm, CO_2 from 5 to 14%, and *HC* between 252 and 1096 ppm. Waste incineration at varying operating temperature levels from 180 to 900°C contributed to mean emissions for *CO*, CO_2 and *HC* ranging from 14 to 5 ppm, 15 to 6% and 1253 to 316 ppm, respectively. The Egerton University dispensary incinerator had the best incineration performance compared to the rest. High moisture contents, overloaded incinerators and low operating temperature levels contributed to high emission levels of flue gases leading to dark and dense smoke which resulted into incomplete wastes combustion indicating poor incineration performance. Wastes incineration at low loading rates, low moisture contents and high operating temperatures produced white and fine bottom ash, low levels of carbon, implying complete wastes combustion.

Keywords: Performance; small-scale incinerators; moisture content; incineration; loading rates; operating temperatures; smoke opacity; bottom ash.

ABBREVIATIONS

ANOVA	*: Analysis of Variance*	μm	*: Micro-metre (millionth of a metre)*
CO	*: Carbon Monoxide*	*PAH*	*: Polycyclic Aromatic Hydrocarbon*
CO_2	*: Carbon Dioxide*	*PCDD*	*: Polychlorinated-dibenzo-p-dioxins (Dioxins)*
COHb	*: Carboxyhaemoglobin*	*PCDF*	*: Polychlorinated-dibenzo-furans (Furans)*
FC	*: Fixed Carbon*	*PM*	*: Particulate Matter*
GHG	*: Greenhouse Gases*	*ppm*	*: Parts per million*
HC	*: Hydrocarbon*	*POPs*	*: Persistent Organic Pollutants*
LSD	*: Least Significant Different*	*SAS*	*: Statistical Analysis of Systems*
MC	*: Moisture Contents*	*TEQ*	*: Toxic Equivalency Quotient*
NEMA	*: National Environmental Management Authority*	*USEIA*	*: United States Energy Information : Administration*
MSW	*: Municipal Solid Waste*	*VM*	*: Volatile Matter*
		VOC	*: Volatile Organic Compound*

1. INTRODUCTION

Solid wastes management remains a big challenge in many parts of the world today. However, there are various disposal methods used to reduce solid wastes such as recycling, open dumping, composting, landfilling, and incineration. Among these methods, solid wastes incineration has become more popular in both industrial and residential environments. The incineration process results in a very significant wastes reduction of mass and volume, odour removal and energy recovery that can safely be disposed of on land, or in underground pits as reported by Astrup et al. [1]. This process involves wastes drying, volatilization, combustion of fixed carbon and char burnout followed by combustion of vapours, gases and driven-off particulate residues as reported by Chang *et al.* [2]. The combustion process depends upon the incinerators design, the air mixture held at high temperatures and producing high combustible gases, long residence/holding time to allow complete oxidation and enough turbulence in the flue gas mixtures as noted by Lombardi et al. [3]. In their study, Petridis and Dey [4] reported that the incineration performance was subject to wastes quantity and quality which varies over time in certain locations due to variability in solid wastes generation and seasonality.

High moisture contents and poor turning of solid wastes will result to incomplete combustion leading to high energy consumption, environmental pollution and exposure risks due to unburnt bottom ash and heavy and dense smoke as noted by Niessen [5]. According to Dong et al. [6], high moisture contents was responsible for the low calorific value, a longer wastes combustion (residence) time in the furnaces as well as combustion instability and low efficiency. The operating combustion temperatures are function of waste heating values, combustion designs, air admissions, and furnaces control which is a function of enclosure materials and char melting temperatures as reported by Kumar et al. [7]. The incinerators overloading can results to poor burndown, causing excessive emissions due to rapid generation of volatile gases leading to overloading of the secondary combustion chambers. The incinerators under-loading on the other hand results in inadequate thermal input and necessitate the use of auxiliary fuel to maintain desired set point temperatures as reported by Tao et al. [8].

The products of incomplete combustion ranges from low molecular weight hydrocarbon emissions such as methane to high molecular weight compound (including dioxins and furans) which causes critical health effect as noted by Wu et al. [9]. The volatile organic compounds (*VOC*) are also products of incomplete combustion and cover wide ranges as they includes carbon chains having high vapour pressures as noted by Quina et al. [10]. The carbon monoxide and hydrocarbon arises in furnace chambers when there are deficiencies of oxygen for full oxidation. The greenhouse gas (*GHG*) which consists of carbon dioxide, nitrogen dioxide, chlorofluorocarbons, methane and ozone may cause sporadic changes in weather patterns and could make parts of the planet unsuitable as noted by Ujam and Eboh [11] hence, its formation should highly be reduced.

The main problems associated with wastes incineration processes are the large volumes of gaseous emission levels which poses serious environmental health risks and hazardous waste remaining after incineration as bottom ashes, fly ash or air pollution control devices residues as reported by Park et al. [12]. The incinerator bottom ashes are highly toxic and handling raises serious concerns to workers who are often exposed, sometimes with little or no protective clothing as reported by Rogers and Brent [13]. Moreover, lack of secure landfills for bottom ashes leads to it being dumped in unlined pits, where it runs the risk of contaminating groundwater and sometimes the dioxin-rich bottom ash find its way into the towns' dumpsites as reported by Guendehou et al. [14]. These problems occur due to non-performance and poorly designed incineration facilities.

This research evaluated factors influencing the performance of small-scale incinerators by incinerating solid wastes at varying: moisture contents; loading/charging rates; and operating temperature levels on flue gas emissions (carbon monoxide, carbon dioxide and hydrocarbon). It also assessed the smoke opacity at the chimneys/stacks and bottom ash residues during solid wastes incineration processes.

2. MATERIALS AND METHODS

2.1 The Study Area and Materials Preparation

This research was conducted using incinerators at Egerton University (Dispensary), Ng'ondu (Janda Plaza), Green Valley (Community Resource Centre) and domestic in neighbouring estates including the Animal Science Nutritional Laboratories (Muffle Furnaces). The map of Egerton University, Njokerio, Ng'ondu and Green Valley estates and incinerators is shown in Fig. 1.

The collection of solid waste samples were from Egerton University dump sites (student cafeterias, hostiles, Departments of Crops, Horticulture and Soil, Animal Health, Human Anatomy, Dispensary) and neighbouring residential estates (Njokerio, Ng'ondu, and Green Valley). The wastes collected were dried for three days, chopped into small pieces and packed separately into waterproof containers in preparation for experimental processes. The reduction of solid wastes sizes to less than one (1) millimetre was necessary in forming homogenous materials leading to increased surface area and allowing faster heat penetration. The waste samples loaded into incinerators were neither pre-treated nor specific ingredient selected. The weighing and recording of all waste samples was done before commencement of incineration processes.

2.1.1 Experimental set-up for the flue gases analyzer

The equipment required in the research included: well-insulated muffle furnace (Lindberg/Blue *MBF51700*); flue gases analyzer (*MS 805*); electronic digital weighing balance; digital electrical meter; alternating current (*ac*) electrical power supply; air flow meter and five working small-scale incinerators. Other facilities were driers, furnace crucibles, timers and shearing/cutting machines plus materials like nose masks, hand gloves and clear goggles.

The flue gases analyzer (*MS 805*) was configured to measure carbon dioxide (CO_2) and oxygen (O_2) depletion levels in percentage (%) while that of carbon monoxide (*CO*) and hydrocarbon (*HC*) in parts per million (ppm). The flue gases analyzing machine is shown in Fig. 2. The flue gases picking-up probes with hoses were firmly fixed to the stack/chimney of incinerators or muffle furnace. The gas samples flowed through the probes of vertical position polymerized filters before reaching the steam traps cups at the bottom of the flue gas analyzer. When gases reached the trap base ducts, it branched into three different pipes where first fittings was into vacuum sensors detecting any possibility of anomalies in gases flowing or leaks in pneumatic circuits. The second pipe connected to sampled gases which were discharged during emissions calibrations and third pipe was connected to gas pumping side through a safety paper filters. The flue gas analyzer had in-built internal measuring sensors for recording the emission levels of CO_2, O_2, CO and HC via the metering bench before being purged out.

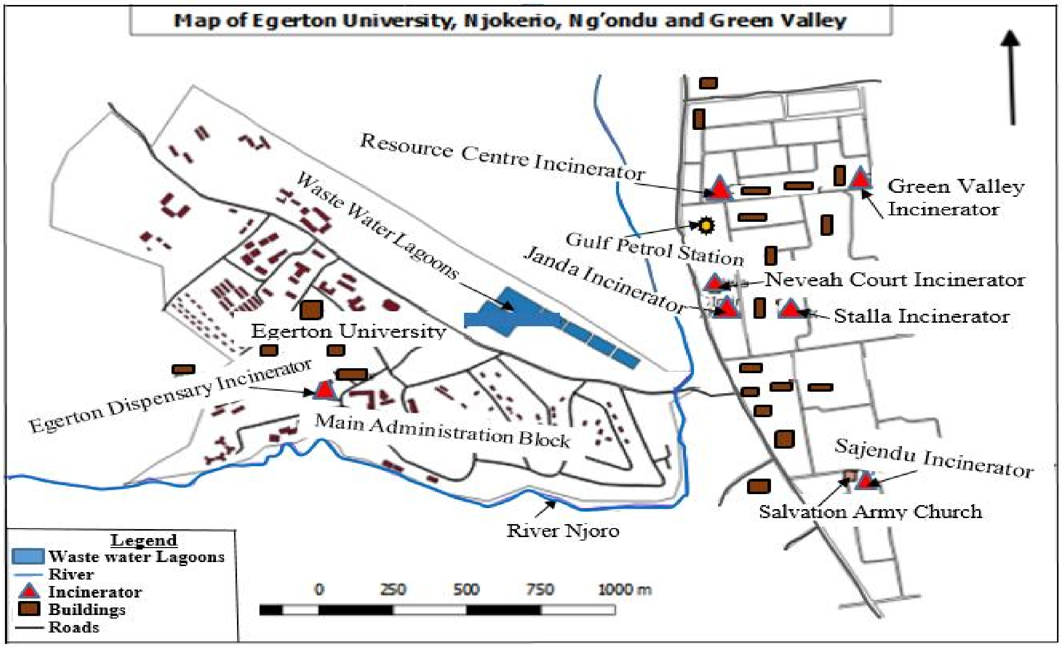

Fig. 1. The study area

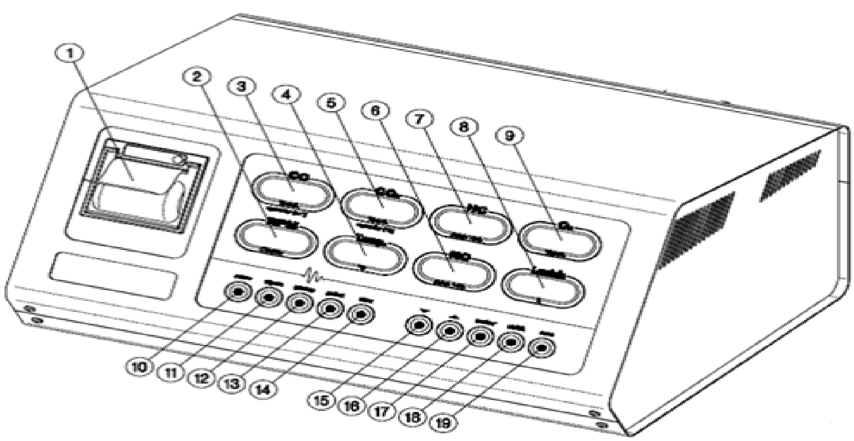

Fig. 2. The flue gases analyzing machine

1- Printer	*5- CO_2 display*	*9- O_2 display*	*13- Print key*	*17- Enter key*
2- RPM display	*6- NO_x display*	*10- Zero key*	*14- Auxiliary key*	*18- Shift key*
3- CO display	*7- HC display*	*11- Calibration*	*15- Cursor key*	*19- Escape key*
4- Temp display	*8- Lambda display*	*12- Pump key*	*16- Cursor key*	

2.1.2 Muffle furnace incineration experimental set-up

The muffle furnace (*Lindberg/Blue MBF51700*) was used for solid wastes incineration at various operating temperature levels since temperature gauge could be regulated. An empty crucible was weighed and residential solid waste samples weighing fifty gramme was poured into it then placed centrally in the combustion chamber and door closed. The muffle furnace power supply was switched on while the flue gases vents were completely opened to remove fully the exhaust gases. The operating temperature levels was adjusted using enter/set arrow keys by pressing 'on' to register the changes. The electrical power 'Run' button was pressed on and the control panel started blinking commencing the operations as shown in Fig. 3. For safety, the incineration of inflammable and explosive waste materials were avoided. Also wastes with high concentrated sulphate, chloride, fluoride alkaline and other combustible substances were kept away due to their corrosiveness on ceramic fibers and explosiveness. The experiments using muffle furnace took maximum of 150 minutes and ten hours cool down.

2.1.3 Solid wastes incineration combustion processes

The incineration combustion processes were done in order to estimate the heating value of solid wastes by determining composition in terms of volatile matters, ash contents, fixed carbon and calorific values. It was represented using Equation 1 as reported earlier [11].

$$C_{x1}H_{x2}O_{x3}S_{x4}Cl_{x5}K_{x6}Ca_{x6}Mg_{x7}Na_{x8} + a_1H_2O + a_2(1 + e)(O_2 + 3.76N_2) \rightarrow a_3CO_2 + a_4H_2O + a_5O_2 + a_6N_2 + a_7CO + a_8CH_4 + a_9NO + a_{10}NO_2 + a_{11}SO_2 + a_{12}HCl + a_{13}HC + a_{14}KCl + a_{15}K_2SO_4 + a_{16}C + \ldots + Heat\ Energy \quad (1)$$

where a_1 corresponds to moisture in the wastes; a_2 relates to air (mixtures of O_2 and N_2);

$1 + e$ is excess air associated to stoichiometric ratios, usually ranged between 1.2 and 2.5;

a_3 to a_{16} corresponds to coefficients of different species found as reaction products.

2.2 Factors Influencing Performance and Emission Levels from Solid Wastes Incineration

The experiments on solid wastes incineration at varying moisture contents and incinerator loading/charging rates were carried out using small-scale incinerators while that of varying operating temperature levels were carried out on a laboratory scale using the muffle furnace. The maximum time of 150 minutes for all the muffle furnace and small-scale incinerators experiments was adopted. According to Park et al. [12], the completeness of wastes incineration processes was regarded complete upon achieving oxygen concentration levels of more than 20.61% in flue

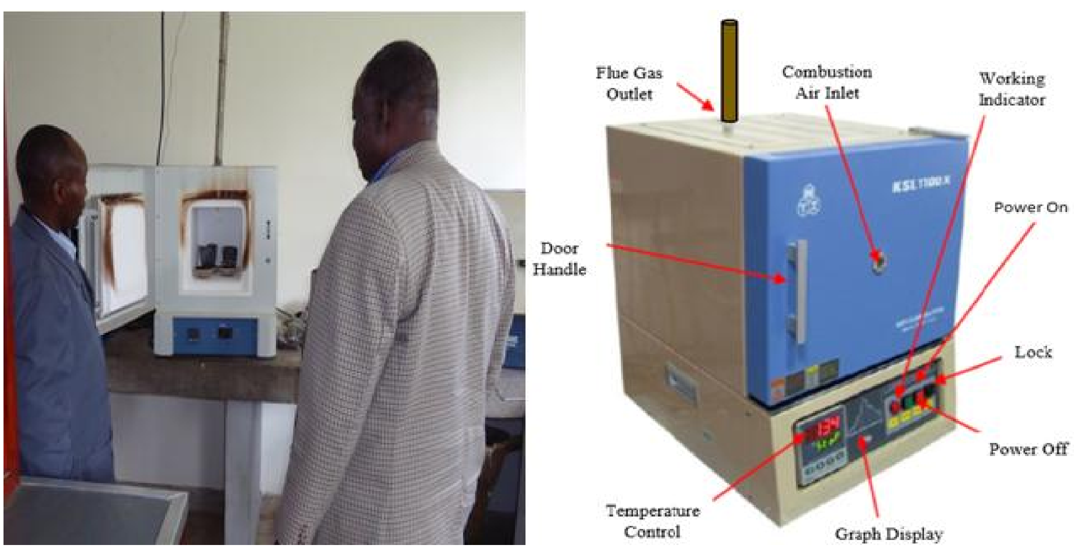

Fig. 3. Muffle furnace incineration equipment

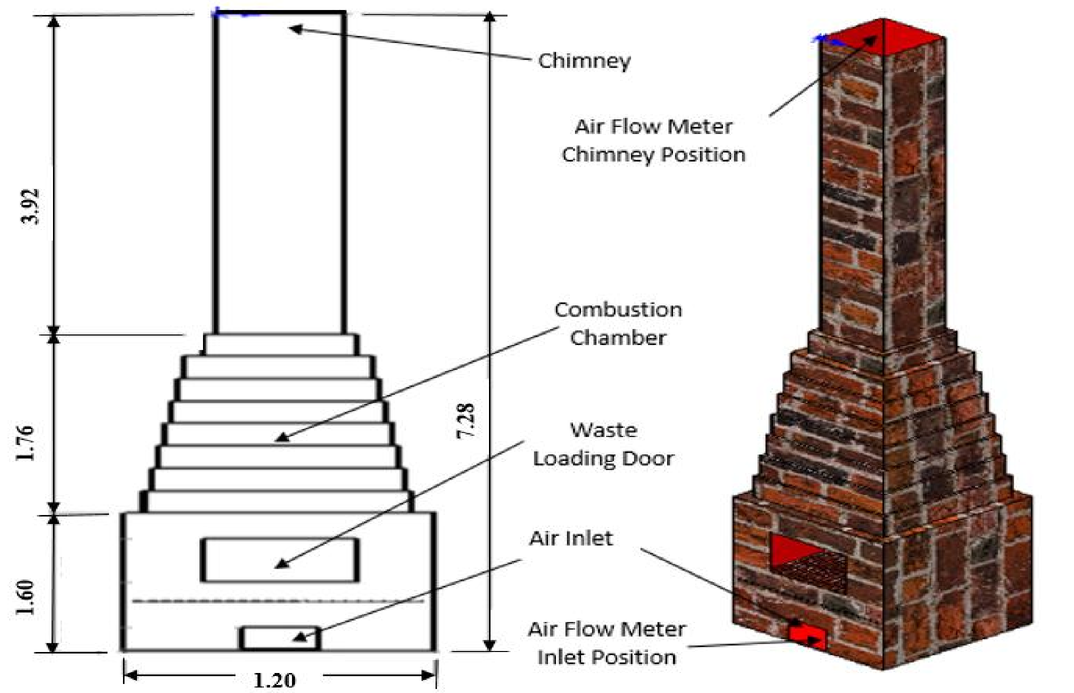

Fig. 4. The small-scale residential solid waste incinerator at Janda Plaza

gases. All experiments were replicated thrice with emissions raw data tabulated in tables, smoke opacity assessments were done and photographs taken while the bottom ash residues was removed and packed for analyses. The small-scale solid wastes incinerator at Janda Plaza opposite the Njoro canning factory where some of the experiments were conducted is shown in Fig. 4.

2.2.1 Effects of solid waste incineration at varying moisture contents on emissions

The effects of solid waste incineration at varying moisture contents (*MC*) on flue gas emission levels were investigated by increasing *MC* from 15% through 75% at intervals of 15% which compared well with the range between 16 and 75% as employed by Katiyar et al. [15]. The different moisture contents were obtained by rewetting and drying of the solid wastes samples. Triplicate samples of solid wastes were constantly dried in ovens at 105°C for twelve hours then cooling done in desiccators and their weights recorded. The waste samples of different moisture contents were thoroughly mixed and separately loaded into the incinerator and furnace ignited. The flue gases passed through the gas analyzer where carbon monoxide, carbon dioxide and hydrocarbon emission levels recording was done for analyses. The same procedures were repeated for the other moisture contents levels.

2.2.2 Influence of waste incineration at varying incinerator loading rates on emissions

The influence of solid wastes incineration at varying incinerator loading rates of 15, 30, 45, 60 and 75 kg/h experiments was performed using Janda plaza incinerator Fig. 4, where its normal maximum solid wastes loading capacity was 45 kg/h. Waste samples of low, medium and high heating values were thoroughly mixed in emulation to normal incinerator loadings. Since the incinerators were manually loaded, it was done when cold. The closing of incinerator doors was important in preventing air infiltrations into the combustion chambers. The flue gas analyzer picking-up probe with their hoses were firmly fixed at the stack/chimney and the power supply switched on. During the solid wastes incineration the carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbon (HC) emissions and oxygen (O_2) depletion levels for each experiment were recorded, smoke opacity assessed and photographs taken for the analyses. The bottom ash residues was removed after cool down to

23°C and packed in well labelled waterproof bags for further analyses.

2.2.3 Effects of wastes incineration at varying operating temperature levels on flue gas emissions

The effects of waste incineration at varying incinerator operating temperature levels experiments on emissions were carried out using well-insulated muffle furnace (Lindberg/Blue *MBF51700*) where its temperature gauges could be adjusted. The solid wastes incineration was conducted at varying operating temperature settings of 180, 360, 540, and 720 through 900°C at intervals of 180°C which compared well with range between 25 and 1025°C as employed by Bradfield [16]. A crucible with fifty gramme solid wastes sample was placed centrally into the combustion chamber and door closed. The flue gases picking-up probe and its hoses were firmly fixed at the stack and muffle furnace and gas analyzer switched on. As flue gases flowed through the gas analyzer, emissions of *CO*, CO_2 and *HC* were recorded and smoke opacity assessed and the bottom ashes was removed for further analyses.

2.3 Assessment of Smoke Opacity at the Chimney

The assessment of smoke opacity was achieved by observing and noting the stack/chimney flue gas emissions when incinerating solid wastes at varying moisture contents, incinerator loading/ charging rates and at operating temperature levels specified in the foregoing sections. The smoke opacity comparisons between dark and dense smoke with excessively particulate matters and light and clear smoke is presented in Fig. 9 in *Chapter three*. The Ringelmann charts was placed approximately 33 metres away, the grid appeared as grey shades, hence quantifying emissions by comparing with the corresponding shade on the charts. The smoke opacity observer stood at sufficient far distance for clear emission viewing with the sun orientation sector at 140 degree to his/her back.

2.4 Assessment of Bottom Ash Residues

The incinerators starting-up commenced with the removal of bottom ashes from previous operational cycles. Incinerators were allowed to cool down for ten hours after the end of each experimental cycle for safely and efficiently bottom ashes removal. The flat blunt shovels were used for cleaning-up, contrary to sharp objects avoiding refractory materials damages. The dropping of the produced ash residues through metallic grills/grates into ash containers at the bottom of furnace was done using mechanically operated stirrers. The ultimate steps in the events was examining the bottom ashes qualities for unburned materials like papers, plastics, woods, food scrapes and its appearances including colours and sizes which was an indication of incineration performance. The collected bottom ashes weight (W_{cb}) at the end of every experimental process was compared with the total wastes loaded (W_{tw}). The bottom ash from different incineration processes was presented in Fig. 10 in *Chapter three*.The wastes combustion processes lost weights (W_r) are calculated using Equation 2.

$$W_r = W_{tw} - W_{cb} \tag{2}$$

The percentage weight reduction P_{wr}, was determined using Equation 3.

$$P_{wr} = \frac{W_{tw} - W_{cb}}{W_{tw}} \times 100 \tag{3}$$

2.5 Analysis of Data

The flue gas emissions raw data were subjected to statistical data analyses using the Statistical Analysis of Systems (*SAS*) (*Software Version 8.02)*. The means and standard deviations were obtained for the flue gas emissions of carbon monoxide, carbon dioxide and hydrocarbon at varying moisture contents; incinerator loading rates; and operating temperature levels. The results were subjected to Analysis of Variance (*ANOVA*) to examine whether they were significantly differences in their means, with Least Significance Difference (*LSD*) performed at 5% level of significance. The mean of each samples means, $\bar{\bar{X}}$ is calculated using Equation 4 as noted by Douglas [17].

$$\bar{\bar{X}} = \frac{\bar{X}_1 + \bar{X}_2 + \bar{X}_3 + \bar{X}_4 + \cdots + \bar{X}_K}{K} \tag{4}$$

where $\bar{X}$ = the mean of each sample and K = the number of samples. The sum of squares for variance between (SS_{btwn}), sum of squares within (SS_{wthn}) and the total sum of squares for variance (SS_{total}) were expressed using Equations 5, 6 and 7 as noted by Kothari [18].

$$SS_{btwn} = n_1(\bar{X}_1 + \bar{\bar{X}})^2 + n_2(\bar{X}_2 + \bar{\bar{X}})^2 + n_3(\bar{X}_3 + \bar{\bar{X}})^2 + \cdots + n_k(\bar{X}_k + \bar{\bar{X}})^2 = \sum\frac{(R_j)^2}{n_j} - \frac{R^2}{n} \tag{5}$$

$$SS_{wthn} = \left\{\sum X_{ij}^2 - \frac{R^2}{n}\right\} - \left\{\sum \frac{(R_j)^2}{n_j} - \frac{R^2}{n}\right\} = \sum X_{ij}^2 - \sum \frac{(R_j)^2}{n_j} \quad (6)$$

$$SS_{total} = \sum X_{ij}^2 - \frac{R^2}{n} \quad (7)$$

where $R = \sum X_{ij}$ the total values of individual items in all the samples; $i = 1,2,3, \ldots$;

$j = 1,2,3, \ldots$; $\frac{R^2}{n}$ = correction factor; and $n =$ the number within samples. The mean square between samples (MS_{btwn}), mean square within samples (MS_{wthn}) and the F-$Ratio$ is expressed using Equation 8 and 9 as noted by Oehlert [19].

$$MS_{btwn} = \frac{SS_{btwn}}{(k-1)} \quad \text{and} \quad MS_{wthn} = \frac{SS_{wthn}}{(n-k)} \quad (8)$$

$$F\text{-}Ratio = \frac{MS_{btwn}}{MS_{wthn}} \quad (9)$$

The statistical outputs were summarized in various tables accompanied by the assessment of smoke opacity and bottom ash residues and were discussed in details in chapter three.

3. RESULTS AND DISCUSSION

This section includes details of experimental work performed on the small-scale solid waste incinerators and muffle furnaces along with the assessments of smoke opacity and bottom ash residues, tables and graphs. The Statistical Analysis of Systems (*Software Version 8.02*) was used to analyse the effects of waste incineration at varying: moisture contents; loading rates; and operating temperature levels on flue gas emissions. The waste incineration experiments were replicated thrice and graphs were generated from statistical data analyses results and discussed based on the means, Least Significant Different (*LSD*) at 5% significant level, *F*-values and the standard deviations.

3.1 Factors Influencing Solid Waste Incineration Performance

This section includes findings of solid wastes incineration at varying: moisture contents; incinerator waste loading rates; and operating temperature levels on flue gas emissions. The incineration of solid wastes was influenced by the sizes, shape of combustion chambers, wall insulations, turbulence levels, loading rates and methods of air injections as reported by Petridis and Dey [4]. The low waste heating values, low temperature levels and lowered turbulence resulted into rising up of residence/holding time to complete combustion process and increased flue gas emissions similar to what Astrup *et al.* [1] reported. The incineration performance was evaluated in terms of flue gas emissions which were carbon dioxide (CO_2), carbon monoxide (CO) and hydrocarbon (HC) including smoke opacity and bottom ash residues assessments.

3.1.1 Influence of wastes incineration at varying moisture contents on flue gas emissions

The moisture content (*MC*) is a non-burnable components in solid wastes which must be kept to a minimum for easier vapourization during the combustion drying phases as reported by Niessen [5]. The unpleasantly odour and associated liquid in the garbage due to putrescible organic components on leftover foods, vegetables, peeled materials and decaying fruits which contaminates and complicates the incineration processes similar to what Bradfield [16] reported. The solid waste incineration processes at varying moisture contents produced the mean carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbons (HC) flue gas emission levels which are presented in Table 1.

Table 1. Mean flue gas emissions at varying moisture contents on waste incineration

Moisture Content (%)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Hydrocarbon (ppm)
15	4.619[a]	5.341[a]	507.92[a]
30	5.744[b]	7.149[b]	688.13[b]
45	7.539[c]	9.743[c]	856.82[c]
60	8.873[d]	11.422[d]	1024.73[d]
75	10.945[e]	13.834[e]	1168.33[e]
Mean of Means	7.544[x]	9.498[y]	849.19[z]

NB: The mean emissions followed by the same letter superscript (a, b, c, d and e) in the same column and mean of means row (x, y and z) are not significantly different at $\alpha = 0.05$

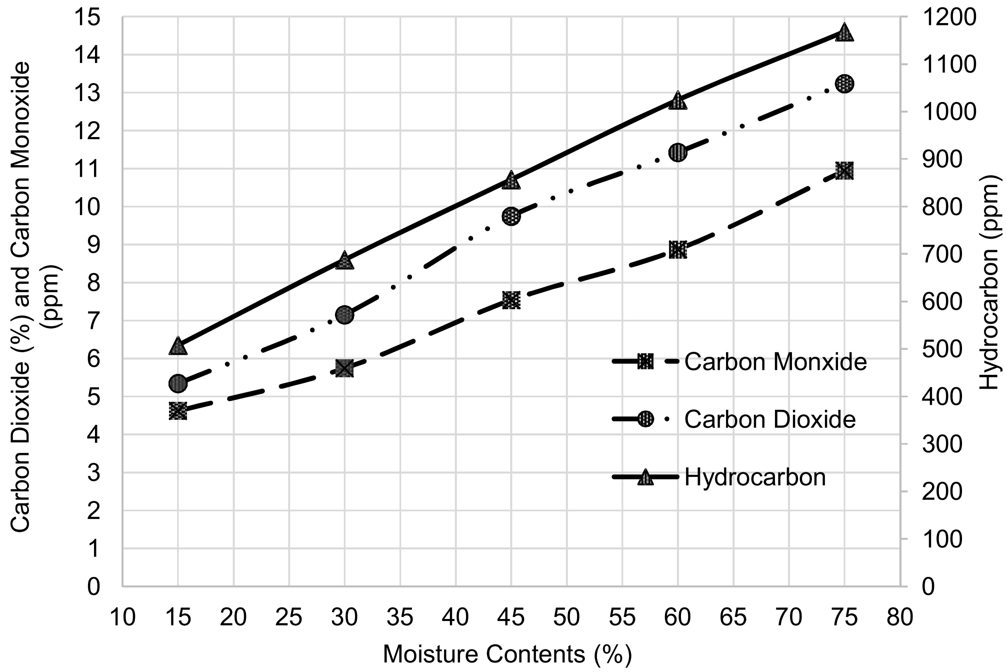

Fig. 5. Effects of moisture contents on emission levels

The means moisture contents with different superscripts letters for *CO, CO_2* and *HC* emission levels in the same column were significantly different at $\alpha = 0.05$ and increased linearly in the *MC* as presented in Fig. 5.

The carbon monoxide (*CO*) is highly poisonous, inflammable, colourless and odourless gas which is slightly soluble in water and slightly lighter than air. The *CO* gas encloses significance energy amount that could be incinerated to produce heat energy and attempts must be made to reduce its creation as reported by Dong et al. [6]. As observed in Fig. 5, the *CO* emission levels increased linearly with increase in moisture contents (*MC*). The increase in *MC* from 15% through 75% led to subsequent increase in the mean *CO* values from 4.6 to 10.9 ppm where the mean of means was 7.5 ppm. These results agreed with the findings by Batterman [20] who stated that *CO* emissions from waste incineration should not exceed mean *CO* of 40 ppm. It also agreed with finding by European Commission [21] that the daily mean *CO* ranged between 5 and 50 ppm for optimum combustion conditions. The mean *CO* emissions increased with the rise of *MC* in the furnace chamber due to water gas reactions.

The carbon dioxide discharged through the incinerator's chimney/stack was influenced by moisture contents in the waste components. The wastes incineration at varying *MC* from 15% through 75% caused mean CO_2 emissions to increase from 5.4 to 13.2% where the mean of means was 9.5% by weight. These results were within the findings by Chen et al. [22] who reported that CO_2 concentrations from flue gases ranged from 5 to 15%. According to Chen and Lin [23], the higher CO_2 emissions, the more efficient are the incineration processes. However, the air to wastes imbalances, furnace misfiring, poor incinerator designs and mechanical faults may decrease the carbon dioxide formation leading to poor incineration performance.

The creation and discharge of hydrocarbon (*HC*) strongly depend on furnace conditions which includes the combustion temperature, residence/holding time, turbulence levels, air/waste ratios, wastes loading rates, moisture contents, carbon to hydrogen ratios in the wastes and materials loading exhibition/mixing ratios as reported by Cheruiyot et al. [24]. Solid wastes incineration at varying moisture contents of 15, 30, 45, 60 and 75% contributed to mean *HC* emissions of 508, 688, 857, 1024 and 1168 ppm, respectively. The results agreed with the findings by Chen et al. [22] that the mean hydrocarbons concentrations at the chimney/stack ranged from 254 to 1970 ppm. The mean *HC* emissions results for *MC* less than 45% were lower than 700 ppm which was within the regulatory standards/limits recommended by Ministry of Environment and Minerals Resources [25]. The high *MC* reduces combustions efficiency leading to high levels of hydrocarbon emissions. Solid wastes containing plastics, polymer, polythene papers and rubber discharged large amount of particulate matters including heavy and dark smoke opacity and high *HC* emissions due to incomplete combustion.

3.1.2 Influence of solid wastes incineration at varying loading rates on gas emissions

The solid wastes incinerator loading/charging rates is also a measure of incineration performance. In this study, the overloading of incinerators resulted into increased flue gas emission levels and incomplete combustion in which the bottom ashes contained unburnt particles while dark and dense smoke at the chimney exit was observed. The oxidization of combustible elements requires higher temperatures to ignite the constituents, mixing of wastes with oxygen, efficient turbulences and adequate time for combustion completeness. The open waste burning processes is where the by-products and materials are burned at lower temperature and in uncontrolledly manner leading to high flue gas emissions. Much of solid wastes open burning is unregulated and is nearly impossible to measure the emission levels as reported by Kumar et al. [7]. The poorly designed small-scale incinerators at Neveah Court and at Sajendu Hostel which resulted into open wastes burning are shown in Fig. 6.

The solid waste incineration processes at varying incinerator loading rates of *CO*, CO_2 and *HC* flue gases emission levels mean values are presented in Table 2. The emission levels increased linearly with increase in waste loading rates.

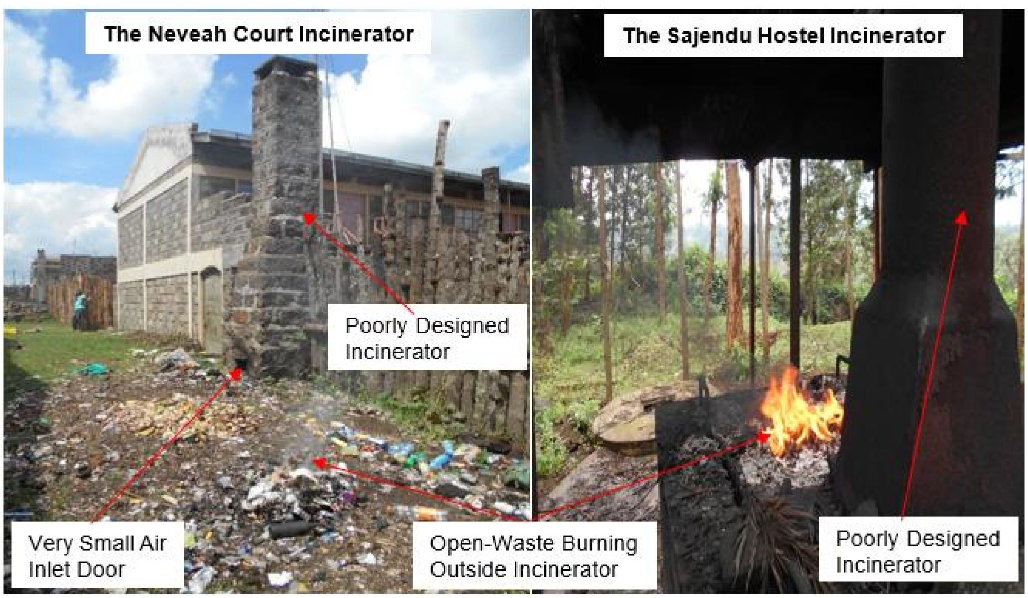

Fig. 6. The poorly designed incinerators resulting to open-waste burning

Table 2. Effects of incinerator loading rates on mean flue gas emissions

Loading Rate (kg/h)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Hydrocarbon (ppm)
15	5.022^{a}	5.428^{a}	252.43^{a}
30	7.474^{b}	8.583^{b}	594.35^{b}
45	9.053^{c}	11.352^{c}	837.12^{c}
60	10.534^{d}	12.963^{d}	993.24^{d}
75	11.784^{e}	13.889^{e}	1096.13^{e}
Mean of Means	8.773^{x}	10.443^{y}	754.65^{z}

NB: The mean emissions followed by the same letter superscript (a, b, c, d and e) in the same column and mean of means row (x, y and z) are not significantly different at $\alpha = 0.05$

The superscripts on means were different in the respective columns implying that increasing incinerator loading rates from 15 through 75 kg/h resulted into significant increase in *CO*, CO_2 and *HC* emission levels towards maxima at around 75 kg/h as illustrated in Fig. 7.

The solid wastes incineration at varying incinerator loading rates from 15 to 75 kg/h resulted into mean *CO*, CO_2 and *HC* emission values ranging from 5.0 to 11.8 ppm, 5.4 to 13.9% and 253 to 1096 ppm, respectively. The results of mean *CO* values agreed with the findings by Astrup et al. [1] that mean *CO* emissions from wastes incineration ranged between 4.5 and 16 ppm. However, these results differed with what was reported by Park et al. [12] that mean *CO* emissions concentration yielded to 94.1 ppm for a large scale sewage sludge incinerator. The differences could be attributed by fact that incinerator used was large scale and a sewage sludge type. According to Quina et al. [10], increasing of *CO* and volatile organic compound (*VOC*) contents in flue gases was a strong indication of inappropriate combustion conditions which agrees with findings of this study. These problems of furnace conditions could be adjusted by increasing the fresh air inlet, reduction of air pressure below the grid as well as recycling of flue gases at the combustion chamber.

In this study, wastes combustion was vigorously characterized by turbulence burning from the high volumes of air with consequently high destruction rates of flue gases. The CO_2 mean values results, agreed with Rogers and Brent [13] who reported that mean CO_2 emissions concentration on flue gases from stack/chimney ranged between 5.4% and 12.7%.

The presences of hydrocarbon (*HC*) emission levels in flue gas are strong indications of incomplete combustion. Loading the incinerators at rates of 15, 30, 45, 60 and 75 kg/h produced mean *HC* emissions of 253, 594, 837, 993 and 1096 ppm, respectively. The outcome agreed with what Wu et al. [9] reported that solid wastes incineration yielded mean *HC* values ranging from 235 to1650 ppm. The mean *HC* emissions results for *loading rate* less than 45 kg/h were within the mean *HC* ambient air quality tolerance limits of 700 ppm as specified earlier [25]. According to Thompson and Anthony [26], the exposure to high levels of *HC* could attack central nervous system, cardiovascular system, foetus and other organs that are oxygen deficiency the same way carbon monoxide do.

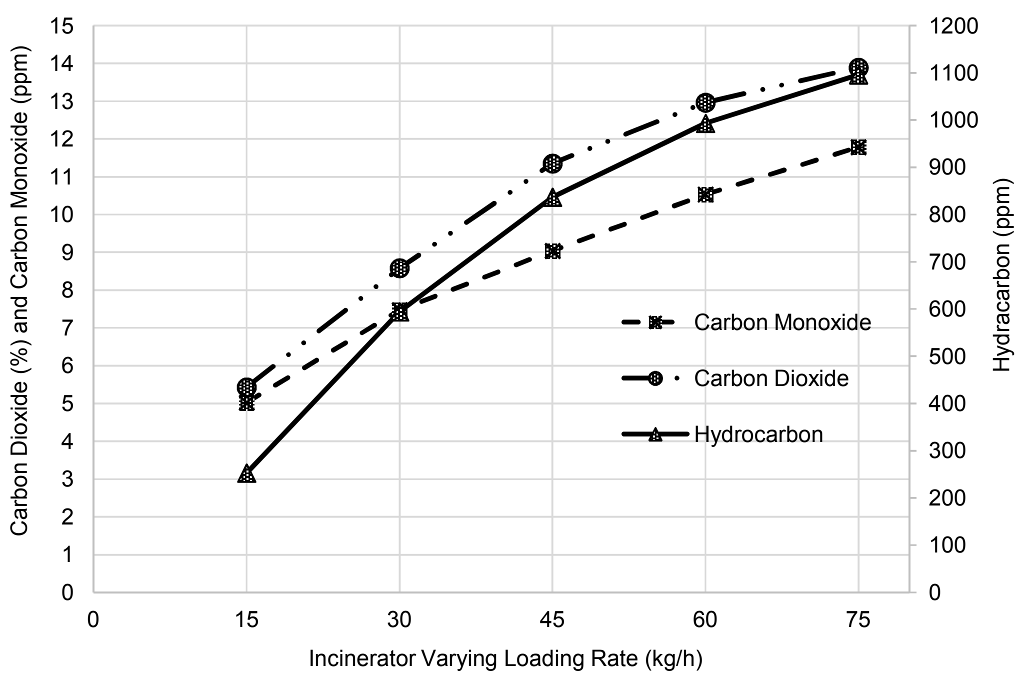

Fig. 7. Influence of incinerator loading rates on gas emissions

3.1.3 Effects of wastes incineration at various operating temperature levels on flue gas emissions

The incinerator operating temperatures is also a measure of incineration performance. The furnace temperatures generation is a function of incinerator unit design, combustion control, air supply, wastes heating values and auxiliary fuels quality. As shown in Table 3, wastes incineration at operating temperature levels ranging from 180 to 900°C was characterized by flue gas emission levels for *CO*, CO_2 and *HC* ranging between 13.7 and 5 ppm, 14.9 and 6.1% including 1253 and 316 ppm, respectively. These results were in agreement with what Lombardi et al. [3] reported.

Since the means superscripts letters are different for *CO*, CO_2 and *HC* in the respective columns in Table 3, it implies that the flue gas emissions are inversely proportional to increase in incinerator operating temperature levels. Hence, increasing the operating temperature from 180 to 900°C caused subsequent decrease in the flue gas emissions as shown in Fig. 8.

The high mean values of *CO* at low operating temperature levels reflected inefficiency of the combustion processes, incomplete organic compounds destructions and energy loss that could have been released for incineration processes. These outcomes were in agreement with the findings published by Quina et al. [10] that mean *CO* emissions from wastes incineration ranged from 5 to 50 ppm. Moreover, the findings disagreed with what Park et al. [12] reported that *CO* concentrations from wastes incineration ranged between 54 ppm and 618 ppm. The differences could have been due to insufficiently air combustion, poor mixing of air/wastes and low incinerator operating temperature levels in the literature. According to Thompson and Anthony [26] the carbon monoxide could be retained by blood haemoglobin stronger than oxygen forming carboxyhaemoglobin (*COHb*), inhibiting oxygen supply to the body tissues.

Increasing the operating temperature levels from 180 through 900°C contributed to mean CO_2 emissions ranging between 14.9 and 6.1% where mean of means was 10.03%. The results agreed with the findings by USEIA [27] who witnessed the mean CO_2 emission levels from solid wastes incineration ranging between 4.2 to 14.9%. Also Chen et al. [22] experienced similar trends where the mean CO_2 emissions reduced from 13 to 5% with increase in incinerator operating temperature levels. Similarly, these results differed with what Astrup et al. [1] reported, that CO_2 produced had a mean value of 18.4%. In their findings, Quina et al. [10] noted that CO_2 increased at high temperature levels due to the release of carboxyl, while *HC* and *CO* were produced instead of CO_2 at low temperatures due to cracking of volatile matters in the wastes.

The solid waste incineration at varying incinerator operating temperature levels from 180 to 900°C produced *HC* emissions values ranging between 1,253 and 316 ppm where mean of means was 800 ppm. The results were within the findings by Cheruiyot *et al.* [24] who reported that mean HC emissions ranged between 1,650 and 278 ppm. Besides, the mean *HC* results for operating temperature above 720°C also were within the ambient air quality tolerance limits of 700 ppm mean *HC* emissions as specified earlier [25]. However, the results differed with what *Conesa et al*. [28] reported that mean *HC* emissions from solid wastes incinerator at 850°C ranged between 117,740 and 4,376 ppm. The difference in emissions could have been due to inadequate waste-to-air mixing ratios and cold spots as well as waste variety, air velocity and combustion mode. The incinerators should work at higher temperatures for complete wastes incinerations and to reduce most of the flue gas emissions.

Table 3. Mean flue gas emissions at various incinerator operating temperature levels

Operating Temp (°C)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Hydrocarbon (ppm)
180	13.743^{a}	14.911^{a}	1253.34^{a}
360	10.456^{b}	11.973^{b}	1049.35^{b}
540	8.157^{c}	9.613^{c}	817.45^{c}
720	6.239^{d}	7.495^{d}	567.03^{d}
900	5.033^{e}	6.133^{e}	316.04^{e}
Mean of Means	8.727^{x}	10.025^{y}	800.642^{z}

NB: The mean emissions followed by the same letter superscript (a, b, c, d and e) in the same column and mean of means row (x, y and z) are not significantly different at $\alpha = 0.05$

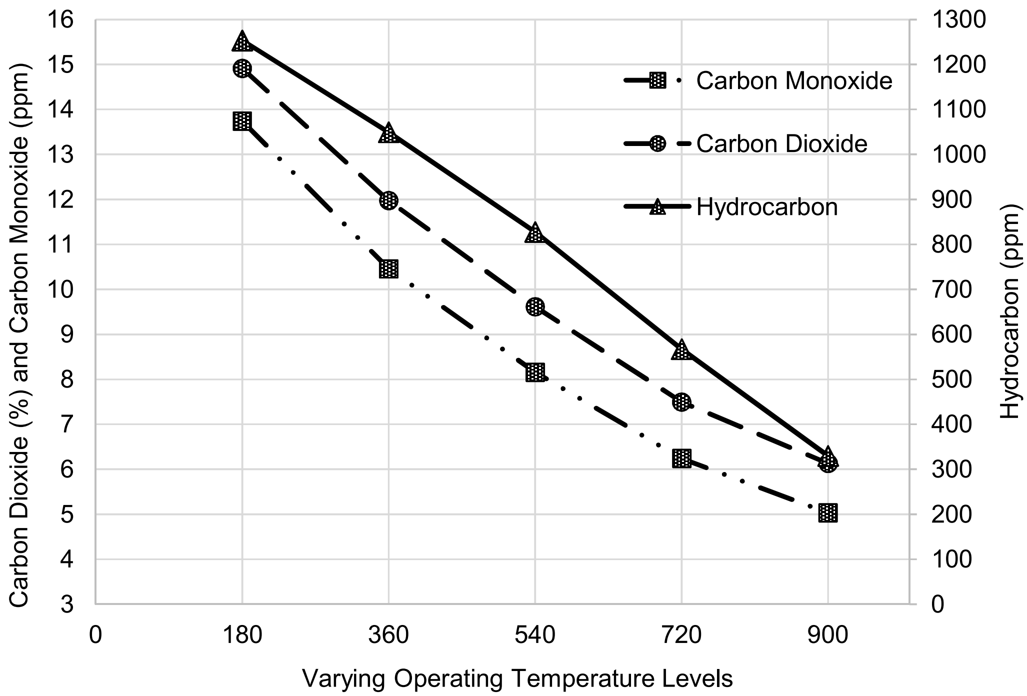

Fig. 8. Effects of incinerator operating temperatures on flue gas emissions

3.2 Assessment of Smoke Opacity at the Chimney

In this research the smoke opacity obtained, provided an indirect measurements of particulate matters concentration in the chimneys/stacks which reflected the incineration performance and compares well with findings reported by Rogers and Brent [13]. The fly ash consisted partially of burned dust-like grey organic matter which according to Reddy et al. [29] represents 10 to 15% of the total ash residues.

As observed from Figs. 5, 7 and 8, high values of moisture contents and incinerator loading rates had direct relations to high flue gas emissions leading to dark and dense smoke but related indirectly to operating temperatures. It was noted that solid wastes from Egerton University contained synthetic resins plus polythene papers, plastic, photocopying papers and rubber which ignited easily releasing less smoke. Also, high values of fixed carbon and low calorific value in wastes could cause maximum smoke opacity to be reached quickly leading to emissions of larger amounts of fine particulate matters within a short time similar to what Ujam and Eboh [11] reported. The smoke of fine particulate matters created due to incomplete waste combustion, would results into respiratory irritations in both animals and human beings as reported by Thompson and Anthony [26]. The incinerators at Community Resource Center and at Green Valley showed dark and dense smoke with excessive particulate matters as shown in Fig. 9.

3.3 Assessment of Bottom Ash Residues

As observed in Fig. 10, the physical and chemical properties of incinerated bottom ash varied with the types, sizes and sources of solid wastes, moisture contents, loading/charging rates and incinerator operating temperature levels.

The results indicated that incinerating wastes at the lowest loading rate of 15 kg/h, least moisture content of 15% and highest incinerator operating temperature level of 900°C produced the finest and grayish bottom ash residues which was an indicator of good incineration performance. As an indicator of ash quality, white or grayish ashes revealed low percentage of carbon remnant in the bottom ashes implying complete wastes combustion. The highest incinerator loading rates of 75 kg/h, high moisture contents of 60% and low operating temperature level of 180°C resulted in bottom ashes which contained large slags and partially unburnt organic matters which were usually black, coarse and sandy in appearance indicating poor incineration performance. It also led to bottom ashes containing large amount of unburned materials (other than incombustible materials such as cans, glass, bottles and scrap metals). Solid wastes incineration at high *MC* of 60% and incinerator loading rate of 75 kg/h contributed to black ashes indicating higher percentage of carbon remains in bottom ashes which agrees with the findings by Guendehou et al. [14] that combustion was incomplete for dark gray and black colour and attributed to unburned contents. According to Chang et al. [2], the PM_{10} concentration may cause severity and respiratory illness such as coughing, aggravated asthma, difficulty in breathing, chronic bronchitis and other lungs malfunctions. Therefore, emissions of PM_{10} into the environment should highly be minimized.

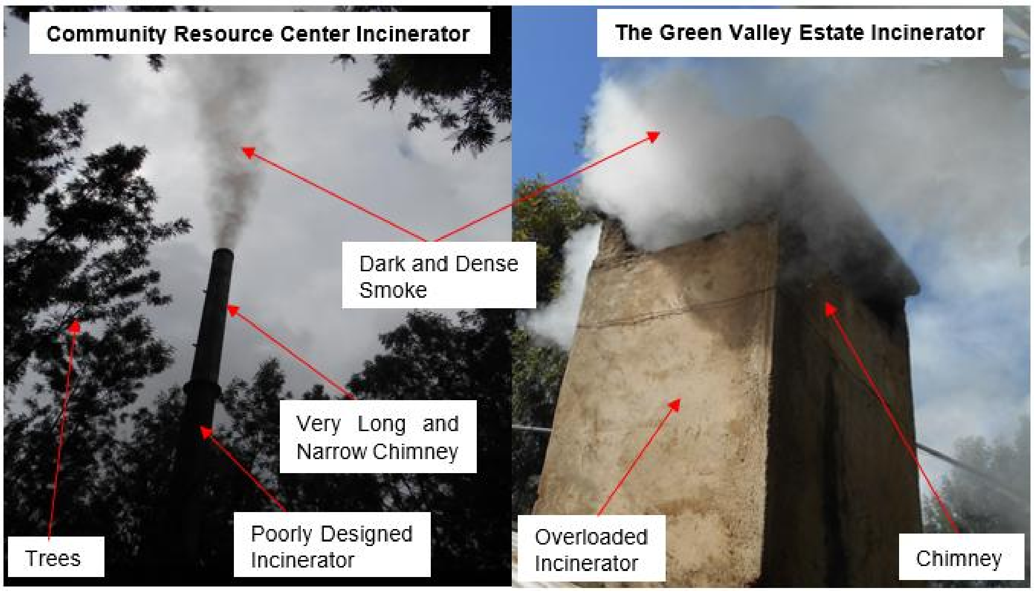

Fig. 9. Incinerators with dense and dark smoke

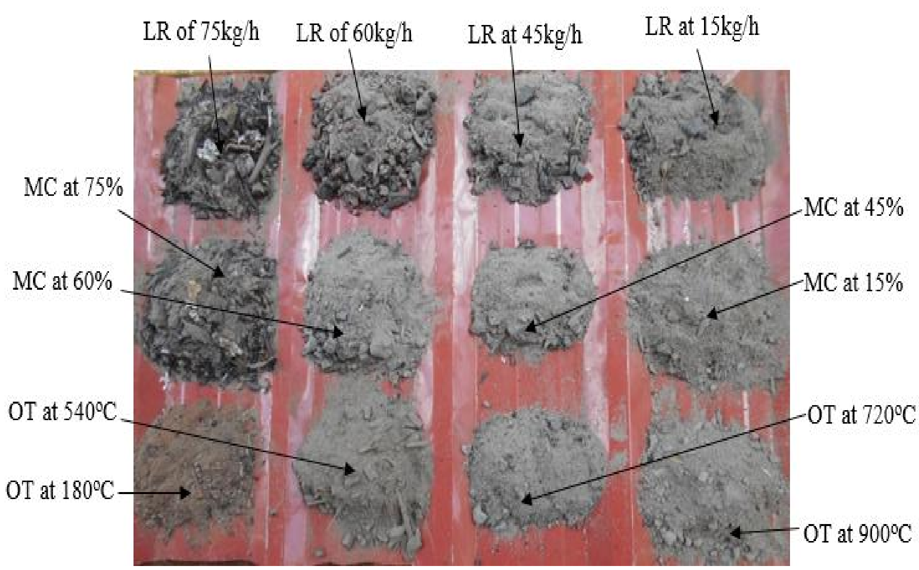

Fig. 10. Bottom ash residues from different experiments

Key: MC- Moisture Contents; LR- Loading Rates; OT- Operating Temperatures

4. CONCLUSION

The solid wastes incineration disposal methods, constituted of complex processes involving economic factors, people's attitudes, governance issues and other such components which contributed to the release of different pollutants into the environment. The results of solid wastes incineration at varying moisture contents, incinerator loading rates, operating temperature levels were determined while the smoke opacity and bottom ash qualities were assessed.

The solid wastes incineration at varying moisture contents (*MC*) from 15 to 75% produced mean flue gas emissions for *CO* from 5 to 11 ppm, CO_2 from 5 to 14% and *HC* from 508 to 1168 ppm. Waste incineration above 45% *MC,* contributed to high *HC* which exceeded the regulatory standards/limits hence, when incinerating very wet solid wastes, the ignition burner should be set to remain on until it is completely burned. The higher moisture contents would prolong the wastes drying processes hence, weakening the combustion processes. There is also need to separate wet putrescible materials in order to increase wastes heating values which in turn reduces emission levels. Wastes incineration at varying incinerator loading rates from 15 through 75 kg/h yielded mean *CO* from 5 to 12 ppm, CO_2 from 5 to 14% and *HC* from 252 to 1096 ppm. Loading the incinerators above the normal wastes loading/charging rates contributed to high *HC* which exceeded the emissions standards/limits and should be avoided. Incinerating wastes at varying operating temperature levels from 180 to 900°C produced mean flue gas emissions for *CO*, CO_2 and *HC* ranging from 14 to 5 ppm, 15 to 6% and 1253 to 316 ppm, respectively. The incinerator operating temperatures above 720°C contributed to low hydrocarbon emissions below 700 ppm which was within the regulatory standards. Therefore, the operating temperature is one of the key variables that determines the combustion conditions and it exert a large influence on emissions formation in the wastes incineration system.

The presence of high levels of *HC* and *CO* in flue gases indicates incomplete combustion, whereas the presence of bottom ashes which contained large pieces of unburned materials is an indication of poor incineration performance. The high values of moisture contents in wastes and high incinerator loading rates contributed to high emissions of flue gases leading to dark and dense smoke but are indirectly related to the operating temperature levels. Solid wastes incineration at low loading rates, low moisture contents and high operating temperature levels produces white, fine and grayish bottom ash which had low percentage of carbon indicating complete waste combustions. Wastes incineration with opposite conditions resulted in course and black bottom ash leading to poor combustion processes. The bottom ashes qualities, physical and chemical properties depend upon waste types, moisture contents, loading rates and operating temperature levels.

The small-scale incinerators cannot fully meet the emissions standards/limits since they are not incorporate with air pollution control devices although, when operated effectively can lower the possible emissions. Some of effective practices includes good incinerator design ensuring combustion conditions were appropriate, detailed construction dimensional plans, and proper operational schedules ensuring appropriate start-up and cool-down procedures. The incineration combustion efficiency improvement through the continuous emission monitoring would reduce the flue gas emission levels and increase the quality of bottom ash residues.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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APPENDIX

Table 4. Mean and standard deviation results from solid waste incineration

Waste Incineration		Carbon Monoxide (ppm)		Carbon Dioxide (%)		Hydrocarbon (ppm)	
	Rep	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**
MC of 15%	3	4.6193	0.1473	5.3414	0.1497	507.923	42.434
MC of 30%	3	5.7446	0.3678	7.1493	0.2715	688.128	59.356
MC of 45%	3	7.5394	0.4351	9.7431	0.5324	856.816	76.173
MC of 60%	3	8.8732	0.5463	11.4224	0.8506	1024.734	92.856
MC of 75%	3	10.9451	0.7347	13.8343	1.2673	1168.336	112.334
LR of 15 kg/h	3	5.0224	0.2132	5.4281	0.2485	252.426	17.286
LR of 30 kg/h	3	7.4743	0.4598	8.5832	0.5277	594.348	48.672
LR of 45 kg/h	3	9.0531	0.6886	11.3524	0.9875	837.119	72.245
LR of 60 kg/h	3	10.5345	0.7743	12.9631	1.1372	993.235	94.863
LR of 75 kg/h	3	11.7842	0.9157	13.8892	1.2313	1096.128	102.128
OTL of 180°C	3	13.7434	1.2136	14.9112	1.2847	1253.343	118.236
OTL of 360°C	3	10.4563	0.8532	11.9734	0.9323	1049.351	94.723
OTL of 540°C	3	8.1571	0.7213	9.6132	0.5217	817.447	79.547
OTL of 720°C	3	6.2392	0.4502	7.4951	0.3602	566.025	46.362
OTL of 900°C	3	5.0334	0.2236	6.1334	0.2351	316.043	22.756

Where: MC- moisture content; LR- loading rate; OTL- operating temperature levels

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