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Concentration of Copper, Zinc, Lead, Cadmium, and Nickel in the Incinerator Bottom Ash in Five County Hospitals in Kenya

Muriithi J. Githinji[1*], Paul M. Njogu[2], Zipporah Nganga[3], Mohamed Karama[4]

[1]Institute of Tropical Medicine and Infectious Diseases (ITROMID), Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya
[2]Institute of Energy and Environmental Technology, Jomo Kenyatta University of Agriculture and Technology (JKUAT), Nairobi, Kenya
[3]Academic, Research and Student Affairs, South Eastern Kenya University, Kitui, Kenya
[4]School of Public Health, Amref International University, Nairobi, Kenya
Email: *jacksongm2020@gmail.com

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Abstract

Healthcare wastes contain potentially harmful microorganisms, inorganic and organic compounds that pose a risk to human health and the environment. Incineration is a common method employed in healthcare waste management to reduce volume, quantity, toxicity as well as elimination of microorganisms. However, some of the substances remain unchanged during incineration and become part of bottom ash, such as heavy metals and persistent organic pollutants. Monitoring of pollution by heavy metals is important since their concentrations in the environment affect public health. The goal of this study was to determine the levels of Copper (Cu), Zinc (Zn) Lead (Pb), Cadmium (Cd) and Nickel (Ni) in the incinerator bottom ash in five selected County hospitals in Kenya. Bottom ash samples were collected over a period of six months. Sample preparation and treatment were done using standard methods. Analysis of the heavy metals were done using atomic absorption spectrophotometer, model AA-6200. One-Way Analysis of Variance (ANOVA) was performed to determine whether there were significant differences on the mean levels of Cu, Zn, Pd, Cd and Ni in incinerator bottom ash from the five sampling locations. A post-hoc Tukey's Test (HSD) was used to determine if there were significant differences between and within samples. The significant differences were accepted at $p \leq 0.05$. To standardize the results, overall mean of each metal from each site was calculated. The metal mean concentration values were compared with existing permissible levels set by the WHO. The concentrations (mg/kg) were in the range of 102.27 - 192.53 for Cu, Zn (131.68 - 2840.85), Pb (41.06 - 303.96), Cd (1.92 - 20.49) whereas Ni was (13.83 - 38.27) with a mean of 150.76 ± 77.88 for Copper, 131.66 ± 1598.95 for Zinc, 234.60 ± 262.76 for Lead, 12.256 ± 10.86 for Cadmium and 29.45 ± 18.24 for Nickel across the five sampling locations. There were significant differences between levels determined by one-way ANOVA of Zn (F (4, 25) = 6.893, p = 0.001, $p \leq 0.05$) and Cd (F (4, 25) = 5.641, p = 0.02) and none with Cu (F (4, 25) = 1.405, p = 0.261, $p \leq 0.05$), Pb (F (4, 25) = 1.073, p = 0.391, $p \leq 0.05$) and Ni (F (4, 25) = 2.492, p = 0.069). Results reveal that metal content in all samples exceed the WHO permissible levels for Cu (100 mg/kg), while those for Ni were below the WHO set standards of 50 mg/kg. Levels of Zn in three hospitals exceeded permissible level of 300 mg/kg while level of Pb exceeded WHO set standards of 100 mg/kg in two hospitals. Samples from four hospitals exceeded permissible level for Cd of 3 mg/kg. This study provides evidence that incinerator bottom ash is contaminated with toxic heavy metals to human health and the environment. This study recommends that hospitals should handle the bottom ash as hazardous wastes and there is need to train and provide appropriate personal protective equipment to healthcare workers, waste handlers, and incinerator operators and enforce compliance to existing regulation and guidelines on healthcare waste management to safeguard the environment and human health.

Keywords

Healthcare Waste, Disposal, Public Health, Environment, Incineration, Heavy Metals, Bottom Ash

1. Introduction

Healthcare facilities (HCFs) are the main healthcare waste generators often referred to as healthcare waste (HCW) medical waste, biomedical waste, clinical waste or health facility waste (Yazie et al., 2019). HCW include all types of waste generated from HCFs, including hazardous, inert materials, infectious non-infectious and chemical (Hasan & Rahman, 2018). It is estimated that HCWs constitute approximately 1% - 2% of total produced urban waste (Dehghani et al., 2019). A total of 85% of all waste generated as a result of healthcare activities is non-hazardous. The remaining 15% are hazardous materials, which are infectious, radioactive or toxic. The majority of HCW generators are hospitals, medical centers, laboratories, veterinary clinics, research centers, mortuaries, blood banks and nursing homes. In low-income countries, HCW is often not segregated into hazardous and non-hazardous waste, making the actual amount of produced hazardous waste much higher (Chartier & WHO, 2014).

Population growth and the outbreak of diseases such as the Ebola virus, severe acute respiratory syndrome (SARS), coronavirus disease of 2019 (COVID-19) and other illnesses have significantly increased medical activities globally (Bucătaru et al., 2021). Unfortunately, medical activities have also contributed to the rising generation of HCW, making it difficult to be managed (Chisholm et al., 2021) especially in developing countries (Debrah et al., 2022). The HCW production rate in countries worldwide differs and depends on many factors. These factors include waste management methods, the type of healthcare facilities, and healthcare specializations, the amount of reusable equipment available in the facility and the number of patients treated daily (Bokhoree et al., 2014). However, registered HCW production is lower in developing countries than in developed countries (Janik-Karpinska et al., 2023).

The improper handling of HCW has hindered achievement of some of the sustainable development goals (SDGs) in most developing countries, specifically good health and well-being (SDG3), clean water and sanitation (SDG6) and climate action (SDG13) (Leal Filho et al., 2022). Considering the significant volume of infectious HCW produced by health facilities in developing countries, the incineration method is currently used to minimize problems posed by infectious waste and consequently negatively impacting public health and the environment (Awodele et al., 2016). Studies in developing countries have shown that incineration reduces the weight of HCW by more than 70% and the volume by 90% (Xiao et al., 2018).

1.1. Healthcare Waste Management Systems

The purpose of healthcare systems is to restore health and save patients' lives, but sometimes adverse effects on the health of healthcare personnel and communities due to unsanitary methods of disposing of HCW is observed (Arab et al., 2008). Poorly managed waste can cause long-term and undesirable risks to public health and is a potential source of re-infection, posing a significant threat to the environment. Therefore, the management of HCW requires special attention and should be considered a high priority (Wafula et al., 2019). The management of HCW is an integral part of national healthcare systems. Safe HCW management practices reflect on HCF service quality and cover all activities related to the generation, segregation, transportation, storage, treatment and disposal of waste (Sahiledengle, 2019). Adequate management of medical waste in HCFs depends on the waste management team, good administration and organization, careful planning, legal frameworks, adequate funding and the full participation of trained personnel in this process (Awodele et al., 2016). Healthcare facilities managers are responsible for introducing and ensuring an appropriate waste management system, as well as supervising the compliance with appropriate procedures of all medical staff. Therefore, appropriate education and training systems must be available to all personnel responsible and engaged in both segregation and waste collection processes (Anozie et al., 2017). In line with WHO guidelines, waste segregation practices should be standardized across the country and included in national regulations for HCW management (Chartier & WHO, 2014). The key to effective management of HCW is the segregation process at the point of waste generation. Segregation means the separation of various types of waste into different colour-coded containers with corresponding coloured liners at places where they are generated as a first step in HCW management (Akulume & Kiwanuka, 2016). According to WHO recommendations concerning segregation and collection, a general waste container should be black. Sharp, infectious and pathological waste containers should be marked yellow. Chemical and pharmaceutical waste container should have a brown colour. It is also recommended that almost all waste categories should be collected at least once per day, or when three-quarters of the container is filled. The exceptions to this are pharmaceutical, chemical and radioactive waste, which can be collected on demand (Pandey et al., 2016).

After segregation, waste is collected and transported outside the hospital or within healthcare facility. The transportation of HCW is usually performed using dedicated trolleys and containers. The trolleys have to be cleaned and disinfected daily. Hazardous and non-hazardous waste has to always be transported separately (Singh et al., 2014). The waste should be stored in designated rooms and appropriate safety and security measures should be taken. In general, non-hazardous, infectious and sharp, pathological, pharmaceutical, chemical and radiological waste should be stored separately in different places with different characteristics depending on the waste stored (WHO, 2017).

1.2. Infectious Waste and Sharps

Infectious waste is a variety of hazardous waste which, due to its pathogenic nature, poses a threat to human health. It should always be assumed that infectious waste may contain various pathogenic microorganisms (Makajic-Nikolic et al., 2016). Pathogens in infectious waste that is not properly managed can enter the human body through damaged skin (rubbing, puncturing or cutting the skin), inhalation, mucous membranes or by ingestion (Chartier & WHO, 2014). The greatest risk of transmission of blood-borne pathogens is caused by needle stick and sharp injuries (NSSIs) (Jahangiri et al., 2016). Healthcare waste can transmit more than 30 dangerous blood-borne pathogens (Yazie et al., 2019) while over 20 other infections can also be transmitted by NSSIs, including syphilis, herpes and malaria. These injuries not only increase the possibility of negative health consequences, but also lead to mental stress, fear, tension and anxiety among healthcare personnel (Ghanei Gheshlagh et al., 2018). The implementation of safety protocols and compulsory training programs for healthcare professionals can reduce the prevalence of NSSIs and associated infections (Matsubara et al., 2017). It can be concluded that this type of waste poses a great potential risk to human health (Udofia et al., 2017).

1.3. Healthcare Waste Treatment and Safety Issues

The most common types of HCW treatments are steam-based treatments (autoclaving, microwave and frictional heat treatments), which are used to disinfect/sterilize highly infectious and sharp waste by subjecting them to moist heat and steam. Steam sterilization is used for sterilization instruments and for sharp and hazardous waste treatments. To reduce the volume of waste, steam sterilization can be combined with mechanical processes, such as mixing, grinding and shredding (WHO, 2017).

Incineration, which involves waste destruction through burning, removes microbiological hazardous materials, reduces their mass and volume and converts them into ashes. An incinerator that is not properly designed or operated, or is poorly maintained, emits toxic substances into the environment. Incinerators operated at low temperatures generate emissions containing carcinogens such as dioxins and furans, which cause health problems (Njagi et al., 2012). Incinerators operating at 850˚C - 1100˚C and containing special gas-cleaning equipment can comply with international emission dioxin and furan standards. Technologies used to control emission of dioxins into the environment use activated carbon (AC) adsorption. Before flue gas flows into the dust-collection equipment, AC is injected to adsorb the dioxin and then is blocked by a bag filter (Padmanabhan & Barik, 2019). Volatile metals, such as mercury, lead, arsenic and cadmium, will damage the immune and neurological systems, as well as the kidneys, brain and lungs. The incineration of high-metal-content materials leads to the spread of toxic metals in the environment (de Titto & Savino, 2019). Adverse health effects in populations in the vicinity of incinerators, including cancer and reproductive dysfunction have been documented (Domingo et al., 2020). Bottom ash analyses of incinerated medical waste carried out in Tanzania indicated the hazardous nature of ash resulting from the presence of large amounts of heavy metals (iron, cadmium, lead, copper and manganese) (Saria, 2016).

The incineration of healthcare wastes not only releases toxic acid gases (CO, CO_2, NO_2, SO_2), dioxides into the environment but also leaves a solid material called ash as residue and includes bottom ash and fly ash which increases the levels of heavy metals, inorganic salts and organic compounds in the environment (Rahman & Singh, 2019). In an effort to justify a projected management and disposal method, bottom ash is either characterized as dangerous, not dangerous or inert (Gidarakos et al., 2009). A few epidemiological studies in developed countries have shown that incinerator workers/operators and residents closer to incinerators (<10 km) presented with diseases related to their work environment. These included laryngeal cancer (Michelozza et al., 1998), gastric cancer (Rapiti et al., 1997), liver cancers (Elliott et al., 1996) and urinary mutagen (Landrigan et al., 1987). Other researches also indicate that incinerator operators presented with a significant level of mercury in their hair (Kurttio et al., 1998), lead and cadmium in blood (Wrbitzky et al., 1995) and hexachlorobenzene in blood/urine (Angerer et al., 1992). A study that focused on three dumpsites in Kenya found that environmental pollution from uncontrolled solid waste disposal is of major concern and generates chemicals or pollutants that reach their surroundings, such as soil, groundwater resources, and even the ambient air, because of environmentally unacceptable disposal or failure of lining system in the dumpsites (Mugo et al., 2015).

Developed countries have shifted from incineration of HCW to more environmentally friendly technologies such as microwave, plasma pyrolysis and ionized autoclave, with minimum environmental and fewer health issues, representing less threat to the environment and human health (Zhao et al., 2021). These alternative HCW treatment technologies are rare in low and middle income countries due to financial implications associated with cost and management (Dinis et al., 2022). Although current modern incinerators operate within a temperature range of 850˚C - 1200˚C, the entire ecosystem and human health is still affected because of the composition of HCW which contain metals that are non-biodegradable (Wei et al., 2021). Heavy metals such as Cd, Hg and Pb could cause chronic diseases like cancer and long-term neurological conditions as revealed by recent studies, leading to possible mortality (Tait et al., 2020). Also, these and other heavy metals can leach through the soil and contaminate drinking water (Mukherjee et al., 2021), which is then absorbed by plants, animals, and other organisms in the food chain (Feng et al., 2020). Meanwhile, the accumulated heavy metals cause chronic and acute toxic effects in the various living beings in nature. Composting and vermicomposting (which uses earthworms to consume and recycle the organic waste) are successfully used to break down hospital kitchen waste, as well as other digestible organic and placental waste. Another example of a biological process is the natural decomposition of pathological waste through its burial. Non-hazardous waste should be recycled and regularly collected by the municipalities or transported by the facility to public landfills (WHO, 2017).

Burying medical waste and depositing them in landfills is also dangerous. HCW is almost always contaminated with pathogens, and leaching toxic heavy metals and chemicals from solid medical waste into the soil occurs in poorly designed dump sites and landfills. The leachate can penetrate the soil and contaminate crops, surface and groundwater resources, posing a risk to human health by consuming water. To control the safety of these methods, hydro-geological conditions must be considered. Landfills should have restricted access, control scavenging, use a soil cover regularly, manage waste discharge, and control surface water and drainage (Udofia et al., 2017).

When incomplete combustion occurs, persistent organic pollutants (e.g., polychlorinated dibenzo-dioxins, polychlorinated dibenzo-furans, and polychlorinated biphenyls) might be formed (Themba et al., 2023). Polycyclic aromatic hydrocarbons (PAHs), which are formed during incomplete combustion and are present in bottom ash (Githinji et al., 2024) in the environment, have low biodegradability and are highly carcinogenic to humans (Abdel-Shafy & Mansour, 2016). A study of bottom ash from healthcare waste incineration in Taiwan region found that the sum of the amounts of PAHs (ΣPAHs) ranges from 162 to 3480 $\mu g \cdot kg^{-1}$ (Lee et al., 2002), and in a study of bottom ash obtained from another healthcare waste incinerator, the sum of the amounts of 11 PAHs was found to be 449.3 μg·kg^{-1} (Wheatley & Sadhra, 2004).

Heavy metals in healthcare waste are usually not destroyed by the incineration process but they are concentrated in the bottom ash. Heavy metals in bottom ash come from various sources, such as zinc (Zn) from batteries, nickel (Ni) from stainless steel needles, and the presence of chromium (Cr), which may indicate the existence of plastic in healthcare waste organics (El-Amaireh et al., 2023). The concentrations of heavy metals vary enormously from study to study, according to (Javied et al., 2008). This variation is due to two reasons: first, incineration operating parameters (furnace temperature, furnace type, and capacity), second, the nature of healthcare waste fed to the incinerator, and third, the experimental parameters for heavy metals content analysis (sample preparation and analytical method) (El-Amaireh et al., 2023). In another study, incinerator bottom ash samples were collected from four hospitals in Ghana and analyzed using atomic absorption spectroscopy (AAS) to measure the concentration of heavy metals (Amfo-Otu et al., 2015). The analysis showed that lead (Pb) and chromium (Cr) were present in large amounts in the samples, with average concentrations of 108.59 and 33.1 mg/kg, respectively. Mercury (Hg) had a minor concentration in the bottom ash samples. High quantities of Pb, Cr, Zn, and Ni had also been observed in another study by Morocco, where the samples were collected from two different incinerators (Bakkali et al., 2013). On the other hand, iron (Fe) had the highest concentration in studies by (Honest et al., 2020), with a concentration range of 758 - 3148 mg/kg, and nickel was the lowest; bottom ash samples were collected from six healthcare hospitals and analysed using inductively coupled plasma optical emission spectroscopy (ICP-OES). The same results, where iron was the largest concentration, were detected in a recent study from Iraq; the heavy metal content was determined using AAS; iron concentration in the study ranged between 25.3 and 76.6 μg/g. The presence of iron in the bottom ash is because iron is the major element of medical needles (Selman et al., 2021).

Some studies have investigated the relationship between particle size and the heavy metal content of healthcare waste incinerator bottom ash. Fine particles were found to be enriched with lead, whereas medium-to-large particles consisted of iron (Racho & Jindal, 2003; Allawzi et al., 2018). Racho & Jindal (2003) explained these results based on the melting point, where lead has a lower melting point (328˚C), so it would convert totally into small particles of ash. Iron, on the other hand, has a high melting point that may reach 1538˚C; therefore, it cannot melt completely but could break at the incinerator's temperature. The main advantages of incineration treatment are that it reduces the volume and mass of healthcare waste; 70% of mass and 90% of volume; and has been used as an energy generating equipment (Linh et al., 2020) and destroys pathogens and hazardous organics (El-Amaireh et al., 2023). Healthcare waste incineration products can be divided into two main parts. The first part is the waste that is released to the external environment, such as fly ash, carbon dioxide, sulphur oxides, and chlorides. The second part is the ash left in the incinerator, called bottom ash. The ash remaining in the incineration chamber constitutes 75% - 90% of the total ash (Jaber et al., 2021).

Despite of these significant advantages, a serious concern with incinerators is their by-products, including pollutant gases, bottom ash, and fly ash (Linh et al., 2020). Pollutant gases can include toxic and carcinogenic compounds, which is one of the important reasons for the limitations of loading some waste types such as plastic in the incinerator (Beylot et al., 2018). Also, incineration residues such as bottom ash and fly ash are known as hazardous waste due to the concentration of compounds such as heavy metals (Bayuseno & Schmahl, 2011). Every year, million tons of ash are produced in incinerators, and must be properly managed (Gomes et al., 2020), because bottom ash and fly ash contain a significant concentration of heavy metals, which can be an important pollutant in water, soil, and air (Li et al., 2022). Currently, there are large amounts of low-standard medical waste incinerators that are being operated by some rural and urban medical institutions in Kenya like in Tanzania, which lack air pollution control devices and without secondary combustion chamber (Manyele et al., 2022) and without burning temperature regulation devices. On the other hand, Kenyan healthcare waste streams, though may be segregated ends up in the incinerator which lead to a large variation in both calorific value and composition. All these factors contribute to uncompleted combustion of healthcare waste. Thus, the composition and distribution of toxic elements in bottom ash from these incinerators may be quite different from that generated from well-equipped large incinerator.

Therefore, the properties of incinerator bottom ash must be extensively investigated before this type of special waste can be reused. The levels of PAHs in five Kenyan hospitals have been studied and reported by (Githinji et al., 2024). The objective of the current study was to obtain basic information on some heavy metals in healthcare incinerator bottom ash by examining levels of Copper, Zinc, Lead, Cadmium and Nickel in Kenya. This information should be useful for evaluating utilization possibilities. This paper, therefore, presents the results of the investigations that were carried out to determine concentrations of these heavy metals in incinerator bottom ash from the five County hospitals.

2. Materials and Methods

2.1. Bottom Ash Samples for Heavy Metals

Bottom ash samples were collected during the period of March-August 2014 from selected county hospitals, namely; Moi-Voi (1), Makindu (2), Narok (3) Isiolo (4) and Kitale (5). A sample of incinerator bottom ash was collected each month from each of the five selected county hospitals in triplicates. A total of thirty samples were collected from the five County hospital incinerators within the six months' period. Ethical approval for the study was obtained from the Kenya Medical Research Institute's (KEMRI) Scientific Steering and Ethical Review Committee.

2.2. Study Areas

The bottom ash samples were collected from the following locations as presented in Table 1.

Sampling Locations

This included Hospital 1 (3.3833˚S, 38.5667˚E), Hospital 2 (2˚16'30.00"S, 37˚49'12.00"E), Hospital 3 (1.0833˚S, 35.8667˚E), Hospital 4 (0.3500˚N, 37.5833˚E), and Hospital 5 (1.0167˚N, 35.0000˚E).

2.3. Study Design

A cross sectional study design was adopted and samples of bottom ash for the analysis of heavy metals being collected longitudinally for six months with a comparative aspect. Quantitative data was collected.

2.4. Incinerator Bottom Ash Sampling for Heavy Metals Analysis

Portions of 500 g of bottom ash samples were collected each month in triplicates for a period of six months from each hospital and stored in airtight glass bottles and wrapped in foil then transported to the laboratory for processing. Plastic spoons were used to collect ash samples, which were stored in pre-cleaned clear glass bottles. Different plastic spoons were used at different sampling locations to prevent contamination. Samples were clearly labeled, stored and transported to the laboratory for analysis.

2.5. Sample Preparation for Analysis of Heavy Metals

Six ash samples of 50 grams each were picked and dried in an oven at 105˚C for 24 hours after which the samples were ground and homogenised using mortar and pestle. A 2 mm mesh was used to sieve to remove debris; poorly burnt materials such as syringes, needles, glasses and scalpels after which 3 samples of 5 grams each were prepared and analysed as described in (USEPA, 2000). Portions of 2 grams each were weighed and added 7.5 ml concentrated analytical grade nitric acid (HNO_3) and 2.5 ml concentrated analytical grade perchloric acid (HCL) for digestion and heated for 30 minutes at 200 kPa/120˚C. After this, five (5) ml of the analyte was picked and distilled, deionized water (DDW) added and filtered with Whitman paper number 41 using a granulated volumetric flask, and this analyte was topped up to 50 ml using DDW. After acid digestion, samples were left to cool and later transferred to a volumetric flask and topped to the 50 ml mark with DDW. This sample was emptied into labelled plastic bottles ready for analysis for Copper (Cu), Zinc (Zn), Lead (Pb), Cadmium (Cd), and Nickel (Ni) using AA6200 Atomic Absorption Frame Emission Spectrophotometer (AAS), and results read and explanation given. A laboratory prepared blank sample was also analysed (APHA, 1995). The analytical procedure followed the flow presented in Figure 1.

Table 1. Locations of study.

Sample site Code	County Hospital	County	GPS location
MVI (1)	Moi Voi	Taita Taveta	3.3833˚S, 38.5667˚E
MKD (2)	Makindu	Makueni	2˚16' 30.00"S, 37˚49' 12.00"E
NRK (3)	Narok	Narok	1.0833˚S, 35.8667˚E
ISO (4)	Isiolo	Isiolo	0.3500˚N, 37.5833˚E
KTL (5)	Kitale	Kitale	1.0167˚N, 35.0000˚E

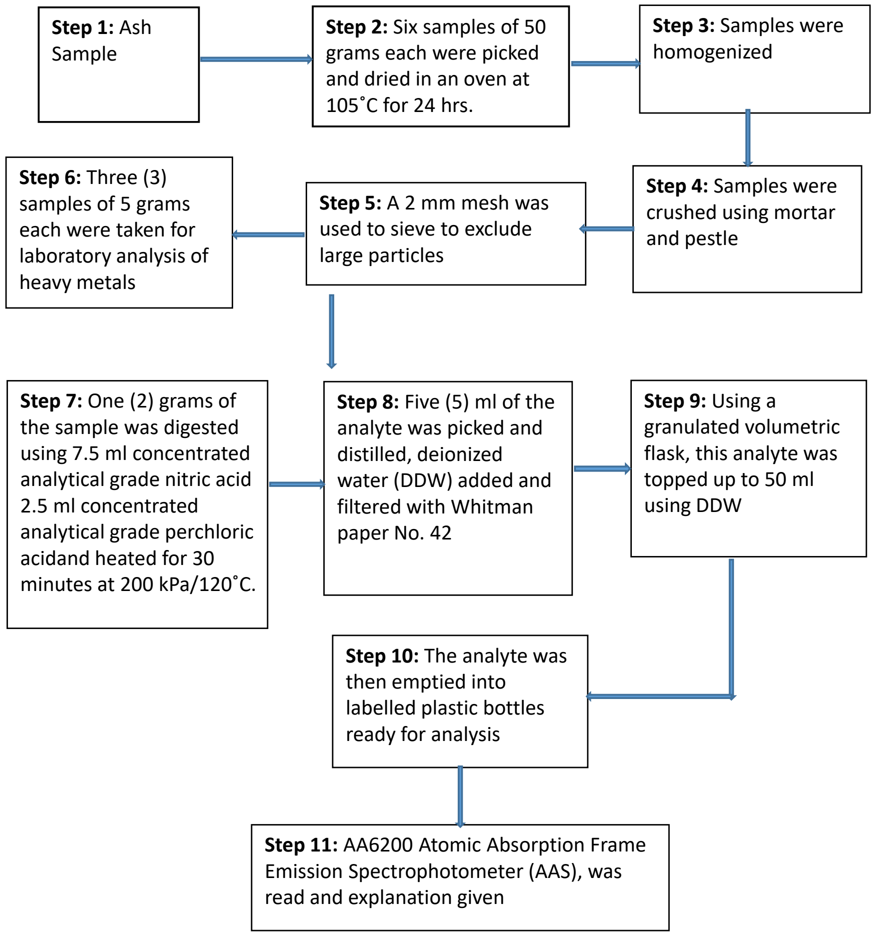

Figure 1. Steps followed during laboratory heavy metal analysis.

2.6. Data Processing and Management

Mean and standard deviation (SD) for heavy metals concentration in bottom ash from the five health care waste incinerators (mg/kg) were calculated. One Way Analysis of Variance (ANOVA) was then performed to determine whether there were any significant differences in the levels of Copper, Zinc, Lead, Cadmium and Nickel in incinerator bottom ash between and within samples. A post-hoc Tukey's Test (HSD) was also performed to determine the significance level of each of the individual metal samples compared to others of same type from other hospitals. The data obtained was analyzed using one-way analysis of variance and significant differences accepted at $p \leq 0.05$.

3. Results and Discussion

3.1. Limits of Detection of Analytical Procedure

The limits of detection of analytical procedure were assessed to determine the validity and reliability of the analytical procedure. The data is presented in Table 2.

Table 2. Limits of detection (LOD) and WHO standards (mg/kg).

Heavy metals	LOD (µg/kg)	Percentage recovery (%)
Cu	1.73	95
Zn	1.38	94
Pb	2.12	97
Cd	0.132	95
Ni	1.30	92

The analytical procedure was found to be reliable since the percentage recoveries were all above 95%. The LODs compared well with those indicated by equipment manufacturer.

3.2. Copper Concentrations (mg/kg) in Incinerator Bottom Ash at Different Sampling Locations

All the five County hospitals had higher concentration levels of Cu from the incinerator bottom ash when compared to the WHO maximum permissible level (100 mg/kg) and therefore with a potential to cause harm to human and the environment (Table 3). There was no significant difference between the means of Cu concentration levels in the incinerator bottom ash from the five County hospitals as determined by one-way ANOVA ($F(4, 25) = 1.405$, $p = 0.261$), $p \leq 0.05$). A post-hoc Tukey's Test (HSD) provided an opportunity for a multiple comparison of Cu mean concentration levels among individual samples in the incinerator bottom ash from the five (5) sampling locations. However, there was no significant difference noted among Copper samples from all the sampling locations, $p \leq 0.05$.

Table 3. Copper concentrations in incinerator bottom ash (mg/kg) at different sampling points.

County Hospital Code	Range (mg/kg)	Mean ± standard deviation	Comparison with WHO maximum permissible level (100 mg/kg)
1	87.53 ± 36.71 - 180.84 ± 19.59	125.24 ± 32.64	Above permissible level
2	69.24 ± 13.13 - 155.00 ± 47.01	102.27 ± 36.70	Above permissible level
3	106.85 ± 12.53 - 215.02 ± 27.39	174.37 ± 62.94	Above permissible level
4	69.32 ± 10.77 - 279.50 ± 13.71	159.40 ± 84.76	Above permissible level
5	120.67 ± 4.01 - 440.81 ± 101.13	192.53 ± 123.13	Above permissible level

The mean levels of Cu ranged from 102.27 ± 36.70 mg/kg to 192.53 ± 123.13 mg/kg, which was detected at County hospital 2 and 5 respectively (**Table 3**). These values of mean levels of Cu are higher than the values by Patra et al. (2017) which was 2.2 mg/kg and still higher than the values for the landfill disposal limits in Singapore which was 100 mg/kg (Patra et al., 2017). The mean Cu concentration levels in this study were also higher than those found in Dares Salaam, Tanzania by Honest et al. (2020) and Saria (2016).

The study found that all the hospitals studied had high concentration levels of copper in the incinerator bottom ash with a mean of 150.76 mg/kg which was above the World Health Organization permissible levels of (100.00 mg/kg) (Chiroma et al., 2014). Elevated exposure to high concentration levels of Cu can result in toxicity of gastrointestinal and hepatic systems (ATSDR, 2022). Honest et al. (2020) reported that Cu compounds for example $CuSO_4$ are used in agricultural activities and can be used as fungicides, insecticides, bactericides, pigments. Also Cu compounds can find its application in wood preservatives and electroplating.

3.3. Zinc Concentrations (mg/kg) in Incinerator Bottom Ash at Different Sampling Locations

Hospital 1 had the highest Zn mean concentration levels of ($\bar{x}$ = 2840.85 ± 925.86, SD = 2267.90) in the incinerator bottom ash as compared to hospital 3 which had the least (131.68 ± 40.96, SD = 100.32) (**Table 4**). Hospital 3 and 4 had Zn concentration levels below WHO maximum permissible limits (100 mg/kg). Hospital 5 (977.95 mg/kg), hospital 2 (2470.06 mg/kg) and hospital 1 (2840 mg/kg) had higher Zn concentration levels as compared to the WHO permissible limits in soil (300.00 mg/kg). High Zn mean concentration levels from samples collected from two different incinerators of 3638.37 and 8236.26 mg/kg were also observed in a study done in Morocco (Bakkali et al., 2013). Zinc is an essential nutrient in humans and animals and its deficiency in human has been associated with dermatitis, anorexia, growth retardation, poor wound healing, hypogonadism with impaired reproductive capacity, impaired immune function, and depressed mental function. Increased incidence of congenital malformations in infants has also been associated with zinc deficiency in the mothers (Cotran et al., 1989). However, an acute oral dose of Zn may cause symptoms such as tachycardia, vascular shock, dyspeptic nausea, vomiting, diarrhoea, pancreatitis and damage of hepatic parenchyma (Roney et al., 2006). The levels of Zn mean concentration found in incinerator bottom ash from hospitals 5, 2 and 1 were above permissible mean concentration and therefore pose a threat to human health and the environment. There was a significant difference between the means of Zn concentration levels in the five County hospitals as determined by one-way ANOVA (F (4, 25) = 6.893, p = 0.001), $p \leq 0.05$. A post-hoc Tukey's Test (HSD) showed clear significant differences among individual samples of Zn, ($p \leq 0.05$), between Hospital 1 and 3 at $p = 0.005$ and between Hospital 1 and 4 at $p = 0.005$. The significant difference between hospital 2 and 3 at $p = 0.017$ and between Hospital 2 and 4 at $p = 0.02$. However, there was no significant difference noted in all the samples analyzed from hospital 5.

Table 4. Zinc concentrations in incinerator bottom ash (mg/kg) at different sampling points.

County Hospital Code	Range (mg/kg)	Mean ± standard deviation	Comparison with WHO maximum permissible level (300 mg/kg)
1	5.11 - 5079.67	2840.85 ± 2267.90	Above permissible level
2	1789.93 - 3784.67	2470.06 ± 719.50	Above permissible level
3	11.54 - 220.21	131.68 ± 100.32	Below permissible level
4	1.76 - 262.14	172.75 ± 95.86	Below permissible level
5	3.42 - 2539.63	977.95 ± 1170.93	Above permissible level

Zinc metal with a melting point of 419.5˚C gives an indication that the type of incinerators used in the three hospitals (5, 2 and 1) burned waste below these temperatures and therefore leaving most of Zn metal within the ash (Honest et al., 2020). The three hospitals used a brick type of an incinerator (De-montfort) which had no temperature regulation gauge and therefore difficult to estimate the temperature used for incineration of waste (**Table 3**). Large amount of Zn when emitted into the environment affects ecosystems as well as living organisms (Zhang et al., 2012). Zinc is one of the toxic heavy metal that is present in healthcare waste as large amounts of Zn may cause stomach cramps, nausea and vomiting. It can also cause anemia, pancreas damage, and lower levels of high density lipoprotein cholesterol (beneficial cholesterol). Breathing large amounts of Zn can cause a specific short-term disease called metal fume fever, especially found in bandages or needles. The concentration levels of Zn observed in this study was lower than the one found in Tanzania 349.367 ± 10.053 to 3047.588 ± 1303.801 mg/kg (Saria, 2016).

3.4. Lead Concentrations in Incinerator Bottom Ash (mg/kg) at Different Sampling Locations

Lead mean concentration in incinerator bottom ash at different sampling locations depicted hospital 1 as the location with the highest mean of (303.96 ± 67.99, SD = 166.52) on the level of Pb on the incinerator bottom ash as compared to hospital 3 which had the least (41.06 ± 11.76, SD = 28.80) (**Table 5**). Four out of five (80%) hospitals exceeded the WHO international permissible levels for Pb in soils and recorded Pb mean concentration in the incinerator bottom ash as follows; Hospital 4 (301.13 mg/kg), hospital 5 (279.72 mg/kg), hospital 2 (247.17 mg/kg) and hospital 1 (303.96 mg/kg). In another study in Ghana (Amfo-Otu et al., 2015), where samples of bottom ash were collected from four incinerators and analyzed using atomic absorption spectroscopy (AAS), Pb was present with mean concentrations of 108.59 mg/kg which was below the WHO allowable limit. However high quantities of mean Pb concentration of 1043.67 and 862.60 mg/kg were observed in a study in Morocco where the samples were collected from two different hospital waste incinerators (Bakkali et al., 2013) qualifying the fact that concentrations of heavy metals vary enormously from study to study (Jung et al., 2004). This variation could be due to: first, incineration operating parameters (furnace temperature, furnace type, and capacity), second, the nature of medical waste fed to the incinerator, and third, the experimental parameters for heavy metals content analysis (sample preparation and analytical method) (El-Amaireh et al., 2023).

Table 5. Lead concentrations in incinerator bottom ash (mg/kg) at different sampling locations.

County Hospital Code	Range (mg/kg)	Mean ± standard deviation (mg/kg)	Comparison with WHO maximum permissible level (100 mg/kg)
1	121.20 - 509.01	303.96 ± 166.53	Above permissible level
2	9.33 - 896.45	247.14 ± 327.84	Above permissible level
3	2.53 - 70.49	41.06 ± 28.80	Below permissible level
4	38.10 - 972.34	301.13 ± 398.91	Above permissible level
5	71.60 - 686.80	279.72 ± 215.925	Above permissible level

These levels of Pb in incinerator bottom ash from the four county hospitals pose potential hazards to human health and the environment. There was no significant difference between the means of Pb in the five hospitals as determined by one-way ANOVA ($F(4, 25) = 1.073$, $p = 0.391$), $p \leq 0.05$. A post-hoc Tukey's Test (HSD) was done on individual Pb samples in the incinerator bottom ash from the five hospitals. However, there was no significant difference noted in any of them ($p \leq 0.05$).

The findings of this study on Pb concentration concurs with Tong et al. (2000) who indicated that developing countries continue to have public health problems when such concentration of Pb are disposed into the environment (Tong et al., 2000). This study found that only one (20%) of the sampling locations (Hospital 3) recorded lower mean concentration levels of Pb (41.06 ± 28.80 mg/kg) in the incinerator bottom ash when compared to WHO maximum permissible limit in soil (100.00 mg/kg). Lead is a well-known neurotoxin and is known to cause impairment of neurodevelopment in children. Exposure in uterus, during breastfeeding and in early childhood may all be responsible for the effects. Lead accumulation in the skeleton and its mobilization from bones during pregnancy and lactation causes exposure to fetuses and breastfed infants with the consequences of increased risk for miscarriage, cause the baby to be born too early or too small, hurt the baby's brain, kidneys, and nervous system and cause the child to have learning or behavior problems (ATSDR, 2020).

According to Loh et al. (2016), Pb is toxic to the human body when exposed to amounts greater than the maximum allowable limits with children being at a higher risk of poisoning. Pb becomes more severe if children come into contact with dust laden with environmental Pb (Loh et al., 2016). Hospitals incinerated sharps which consisted of needles and plastic syringes and therefore it was not surprising that the Pb content was high. Even though sharps were also burnt in incinerators, they were normally mixed with other combustible waste which probably contributed to the level of Pb in the ash residue. Exposure to elevated levels of lead has been associated with numerous adverse effects on renal function, development and reproduction in animals and humans (Pirkle et al., 1998).

3.5. Cadmium Concentrations in Incinerator Bottom Ash (mg/kg) at Different Sampling Locations

Hospital 1 had the highest mean Cd concentration levels in incinerator bottom ash at different sampling locations (20.49 ± 7.49, SD = 18.86) as compared to hospital 5 which had the least (−1.92 ± 0.95, SD = 2.33) (**Table 6**). Four (80%) of the hospitals studied that included, hospital 1 (20.49 mg/kg), hospital 2 (11.77 mg/kg), hospital 3 (14.26 mg/kg) and hospital 4 (12.83 mg/kg) had higher levels of Cd as compared to the WHO permissible levels in soil (3.00 mg/kg). This mean concentration level of Cd from samples analyzed in this study were higher than those observed from samples from two incinerators of 0.73 and 3.81 mg/kg respectively (Bakkali et al., 2013). This study used Atomic Absorption Flame Spectrophotometer (AAS) while (Bakkali et al., 2013) used inductively coupled plasma–optical emission spectroscopy. The mean concentration of Cd observed in incinerator bottom ash from the four county hospitals were two to three times higher when compared to WHO permissible limits and therefore posed a risk to human health and the environment. There was a significant difference between the mean concentration levels of Cd in incinerator bottom ash across the five sampling locations as determined by one-way ANOVA (F (4, 25) = 5.641, p = 0.002, $p \leq 0.05$. A post-hoc Tukey's Test (HSD) showed that there were significant differences in Cd samples between Hospital 1and 5 at $p = 0.001$, Hospital 3 and 5 at $p = 0.022$ and between Hospital 4 and 5 at $p = 0.042$, $p \leq 0.05$. However, there were no significant difference noted in all the samples tested from hospital 2, $p \leq 0.05$.

Table 6. Cadmium concentrations in incinerator bottom ash (mg/kg) in different sampling locations.

County Hospital Code	Range (mg/kg)	Mean ± standard deviation	Comparison with WHO maximum permissible level (3 mg/kg)
1	11.19 - 57.73	20.4900 ± 18.35143	Above permissible level
2	7.60 - 16.49	11.7700 ± 3.17812	Above permissible level
3	11.30 - 18.56	14.2650 ± 2.53065	Above permissible level
4	11.67 - 14.04	12.8317 ± 0.89137	Above permissible level
5	0.27 - 4.41	1.9200 ± 2.33026	Below permissible level

Cadmium was present in all the five incinerators studied. However, it was found to be higher compared to WHO permissible levels in soils (3.00 mg/kg) except in hospital 5 where the amount was lower (1.92 mg/kg). This means the current levels of Cd in incinerator bottom ash from the other four (80%) sampling locations (hospitals 1, 2, 3 and 4) are of public health concern since the levels pose a threat to the environment and human health. The mean concentration of Cd from the five sampling locations was 12.26 mg/kg which was four times higher than WHO permissible levels in soils (3.00 mg/kg). Human beings get poisoned by Cd through ingestion of food, breathing contaminated air, or drinking water rich in the metal. Cd is recorded not to have any attribute that is helpful to plant growth metabolic processes (Hayat et al., 2018). High exposure to humans may lead to obstructive lung disease and can even cause lung cancer. Cd produces bone defects in humans and animals (Tirkey et al., 2012).

According to Rushton (2003), poor emissions of Cd from healthcare waste incinerators may cause health damage of the immune system, neurological system, lungs and kidneys (Rushton, 2003). Long-term exposure to cadmium through air, water, soil, and food leads to cancer and organ system toxicity such as skeletal, urinary, reproductive, cardiovascular, central and peripheral nervous, and respiratory systems. Cadmium levels can be measured in the blood, urine, hair, nail and saliva samples (Rahimzadeh et al., 2017). The mean concentration levels were higher than those found in other studies that recorded 7.14 mg/kg and 0.011 - 0.019 mg/kg (Honest et al., 2020) respectively.

3.6. Nickel Concentrations in Incinerator Bottom Ash (mg/kg) in Different Sampling Locations

Hospital 5 mean concentration levels of Ni in incinerator bottom ash was the highest (38.27 ± 7.57, SD = 18.55) as compared to hospital 2 which had the least (13.83 ± 1.47, SD = 3.61), **Table 7**. All the five sampling locations had low levels of Ni from incinerator bottom ash when compared to the WHO permissible levels, which are set at 50.00 mg/kg. This is in agreement with another study in Tanzania by Honest et al. (2020) and Selman et al. (2021) in Iraq where bottom ash samples were collected from six healthcare centers and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES) and Ni found to have the lowest concentrations (Honest et al., 2020; Selman et al., 2021). This study does not agree with another one done in Morocco where high concentrations of Ni were found from samples collected from two incinerators of 138.35 and 31.14 mg/kg respectively (Bakkali et al., 2013). This variation could be due to: first, incineration operating parameters (furnace temperature, furnace type, and capacity), second, the nature of medical waste fed to the incinerator, and third, the experimental parameters for heavy metals content analysis (sample preparation and analytical method) (El-Amaireh et al., 2023). There was no significant difference between the means of Nickel in the five county hospitals as determined by one-way ANOVA ($F(4, 25) = 2.492$, $p = 0.069$, $p \leq 0.05$). A post-hoc Tukey's Test (HSD) of individual Ni samples in the incinerator bottom ash from the county hospitals had no significant difference, $p \leq 0.05$.

Table 7. Nickel concentrations in incinerator bottom ash (mg/kg) in different sampling locations.

County Hospital Code	Range (mg/kg)	Mean ± standard deviation	Comparison with WHO maximum permissible level (50 mg/kg)
1	2.06 - 60.50	20.4900 ± 18.35143	Below permissible level
2	8.30 - 17.78	11.7700 ± 3.17812	Below permissible level
3	11.40 - 49.11	14.2650 ± 2.53065	Below permissible level
4	25.49 - 55.67	12.8317 ± 0.89137	Below permissible level
5	18.06 - 18.97	1.9200 ± 2.33026	Below permissible level

Nickel is a micronutrient essential for proper functioning of the human body, as it increases hormonal activity and is involved in lipid metabolism. This metal makes its way to the human body through respiratory tract, digestive system and skin (Zdrojewicz et al., 2016). Nickel compounds are known carcinogens in both human and animal models (Feder et al., 1996). There is evidence that the genotoxic effects of Ni compounds may be indirect through the inhibition of DNA repair systems. As a result of this inhibition, it has been suggested that accumulation of Ni in breast tissue may be closely related to malignant growth process (Beyersmann, 2002). Accumulation of nickel and nickel compounds in the body through chronic exposure may be responsible for a variety of adverse effects on the health of human beings, such as lung fibrosis, kidney and cardiovascular diseases and cancer of the respiratory tract (Seilkop & Oller, 2003). High incidence of nasal and lung cancer in workers exposed to nickel and nickel compounds has also been observed (Jose et al., 2018).

4. Qualitative Data on the Five Hospitals Studied in Kenya

Quantities of healthcare waste generated in a given hospital ranges widely depending on different factors such as size of the hospital, number of outpatient, number of other departments and number of beds and cots. Hospital 5 with 218 beds and cots, had the highest volume of healthcare waste generated per day (132.98 - 224.54 kg) while hospital 2 with 97 beds and cots generated the least (58.56 - 98.88 kg) (**Table 8**). The result of the investigation reveals that, though, there was segregation taking place at the point of generation of infectious and sharps waste by use of the color coding system, all the waste was collected and transported for incineration. All the incinerators assessed in this study across the five hospitals were not equipped with Air Pollution Control (APC) systems which agrees with another study done in Ghana (Dominic, 2016). The financial implications of cost and management of these alternative HCW treatment technologies discourages their use. As a result, lots of noxious organic and inorganic pollutants that are injurious to human health are released in the flue gas (Adu et al., 2020).

The HCW generation rates of between 0.61 kg/bed/day to 1.03 kg/bed/day as documented in a study done in Kenyan hospitals were used to calculate the total HCW generated·day^{-1} (kg) (Nkonge et al., 2014).

Table 8. Qualitative data on the five hospitals studied in Kenya.

Hospital No.	Total No. of beds and cots	NO. of beds and cots occupied·day^{-1}	HCW generated per bed·day^{-1} (kg)	Total HCW generated·day^{-1} (kg)	Total HCW generated·year^{-1} (Tons)	Type of Incinerator
1	112	105	0.61 - 1.03	64.05 - 108.15	23.38 - 39.48	Demontfort
2	97	96	0.61 - 1.03	58.56 - 98.88	21.37 - 36.09	Demontfort
3	170	163	0.61 - 1.03	99.43 - 167.89	36.30 - 61.28	Diesel fired
4	248	174	0.61 - 1.03	106.14 - 179.22	38.74 - 65.415	Diesel fired
5	250	218	0.61 - 1.03	132.98 - 224.54	48.54 - 81.96	Demontfort

5. Conclusion

1) This study reveals that the levels of 80% of the metals assessed (Copper, Zinc, Lead, and Cadmium) were above WHO maximum permissible levels while Ni was lower.

2) The incinerator bottom ash studied showed that Cu levels in all the hospitals were above the WHO standards (100 mg/kg). Three hospitals (1, 2 and 5) recorded Zn levels that were above WHO standards. All the hospitals except hospital 3 had Pb levels above WHO standards. All hospitals recorded high levels of Cd than WHO standards except hospital 5 while all the hospitals met Ni WHO standards.

3) The incinerator bottom ash should be classified as hazardous and should not be disposed by landfilling due to the observed high level of concentrations of heavy metals that were above acceptable maximum limits.

4) Incinerators operation temperatures could not be recorded due to lack or defective temperature regulation gauges in all the sampling locations.

Recommendations

1) The anticipated continuous exposure to heavy metals in incinerator bottom ash to healthcare waste workers, waste handlers, incinerator operators and the community may pose direct health risk and should be mitigated.

2) To minimize the impact of incinerator bottom ash to human health and the environment, waste minimization, purchasing strategy and inventory control should be adjusted. Goods with short expiry dates should be rejected.

3) There should be a deliberate training of all actors along HCW management chain and healthcare workers, waste handlers and incinerator operators equipped with PPEs and given the necessary vaccinations.

4) Waste treatment equipment should be revamped to meet the National Environment Management Authority's (NEMA) requirements.

Future Research

1) Studies to establish health impacts of the fly ash and gaseous emissions to the incinerator operators, health workers, waste handlers and the surrounding

communities where healthcare waste is incinerated should be conducted.

2) Studies to establish the health impacts of incinerator bottom ash to the incinerator operators.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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