Determination of Heavy Metal Levels in Hybrid and Indigenous Kamba Maize Seed Varieties from Farms in Masii, Machakos County, Kenya

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ABSTRACT

Maize is a staple food consumed by the Kenyan population; however, heavy metal contamination in maize seeds poses significant health risks. This study determined the levels of lead (Pb^{2+}), cadmium (Cd^{2+}), zinc (Zn^{2+}), copper (Cu^{2+}), and manganese (Mn^{2+}), in three maize seed varieties harvested from Masii Ward, Mwala Sub-County, Machakos County, Kenya. Fresh and dry SC Duma 43 and SC Sungura 301 hybrid with Indigenous Kamba (Kinyaanya) maize seeds, were collected from selected farms in Mbaani, Kathama, and Muthei sub-location in Masii Ward and transported to the Department of Chemistry, University of Nairobi, for analysis. The dried and ground maize seeds were digested using an optimized acid mixture of HNO_3, $HClO_4$, and H_2O_2 in a ratio of 2.5:0.75:0.5 v/v at 105°C for 2.5 hours. The heavy metals were analysed using Atomic Absorption Spectroscopy (AAS). The results showed that zinc levels ranged from 0.343 ± 0.0505 mg/g to 0.389 ± 0.0007mg/g, cadmium from 0.562 ± 0.217 mg/g to 1.998 ± 0.110 mg/g, copper from 0.700 ± 0.0380 mg/g to 0.756 ± 0.101 mg/g, manganese from 0.270 ± 0.0586 mg/g to 2.745 ± 0.851 mg/g, and lead from 8.247 ± 0.798 mg/g to 10.449 ± 0. 398 mg/g. Despite falling below World Health Organization / Food and Agriculture Organization (WHO/FAO), and Kenya Bureau of Standards (KEBS) limits , the detected levels of zinc, copper, and manganese requires monitoring regarding long-term bioaccumulation. Cadmium and lead levels exceeded permissible limits (0.1 and 0.5 mg/g, respectively), with lead concentration particularly high across all three varieties. The analysis revealed that maize seeds pose severe health risks and are unfit for human consumption. This study highlights the urgent need for regular monitoring of heavy metals contamination in food crops and for the implementation on remediation strategies to safeguard public health in Machakos County and similar agricultural regions in Kenya.

Keywords: Heavy metals, Maize seeds, Atomic Absorption Spectroscopy, SC Duma 43, SC Sungura 301, Indigenous Kamba maize, Lead, Cadmium, Food safety, Machakos County.

INTRODUCTION

Maize (Zea mays L.) stands as one of the most important cereal crops worldwide and serves as a primary staple food for billions of people, particularly in sub-Saharan Africa. In Kenya, maize occupies a central position in food security, with the majority of households depending on it as their main source of calories and nutrition. The crop is cultivated across diverse agro-ecological zones in the country, with Machakos County being one of the significant production areas. However, the safety and nutritional quality of maize can be compromised by the presence of heavy metal contaminants, which pose substantial risks to human health and environmental integrity [1].

Heavy metals are defined as chemical elements with relatively high atomic weights and densities that exhibit strong toxic effects even at low concentrations. These metallic elements are persistent in the environment, non-biodegradable, and tend to bioaccumulate in living organisms, making them particularly dangerous environmental pollutants [2]. The primary heavy metals of concern in agricultural systems include lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and manganese (Mn), among others. Their presence in agricultural soils

and subsequently in food crops has become a matter of increasing concern among researchers, public health officials, and policymakers worldwide [2].

The contamination of agricultural soils with heavy metals occurs through various anthropogenic and natural pathways. Industrial activities such as mining, smelting, and manufacturing release substantial amounts of heavy metals into the environment, contaminating both soil and water resources used for irrigation [3]. Agricultural practices themselves contribute to this problem through the long-term application of phosphate fertilizers, which often contain heavy metal impurities, the use of pesticides with metallic components, and the application of sewage sludge as soil amendment. Additionally, atmospheric deposition from vehicle emissions and industrial discharges introduces heavy metals into farmlands, particularly in areas close to urban centres or industrial zones. Natural geological formations in certain regions may also contribute elevated levels of specific heavy metals to the soil [3].

Maize plants are known to be sensitive to heavy metal stress and can absorb these contaminants from the soil through their root systems. Once absorbed, heavy metals are transported to various plant parts, including the grains, where they accumulate to varying degrees. The extent of accumulation depends on multiple factors including the concentration of metals in the soil, the specific metal type, the maize variety, soil pH, organic matter content, and prevailing environmental conditions. Research has demonstrated that different maize varieties exhibit varying capacities for heavy metal uptake and accumulation, with some cultivars showing higher susceptibility than others. Understanding these varietal differences is essential for developing appropriate mitigation strategies and breeding programs aimed at reducing heavy metal accumulation in edible portions of the crop [4].

The health implications of consuming heavy metal-contaminated maize are severe and multifaceted. Lead exposure, even at relatively low levels, has been associated with neurodevelopmental problems in children, including reduced intelligence quotient (IQ), learning disabilities, and behavioural disorders. In adults, chronic lead exposure can lead to hypertension, cardiovascular disease, kidney damage, and reproductive problems. Cadmium, classified as a human carcinogen by international health agencies, accumulates primarily in the kidneys and liver, causing nephrotoxicity, hepatotoxicity, and bone disease. It interferes with calcium metabolism and can lead to osteoporosis and skeletal damage. Both lead and cadmium have been shown to induce oxidative stress, damage deoxyribonucleic acid (DNA), and disrupt multiple physiological systems including the endocrine, cardiovascular, and reproductive systems [4].

While zinc, copper, and manganese are essential micronutrients required for normal physiological functions, their presence in excessive amounts can be equally harmful. Zinc toxicity manifests as gastrointestinal distress, including nausea, vomiting, and diarrhoea, and can interfere with the absorption of other essential minerals such as iron and copper, leading to secondary deficiencies. Excessive copper intake causes liver damage, neurological problems, and can trigger Wilson's disease-like symptoms. Manganese toxicity primarily affects the central nervous system, potentially causing a condition resembling Parkinson's disease, characterized by tremors, difficulty walking, and facial muscle spasms [5].

This research aligns with several United Nations Sustainable Development Goals (SDGs), demonstrating its broader significance beyond immediate health concerns. SDG 2, which focuses on achieving zero hunger and ensuring access to safe and nutritious food, is directly addressed through this study's emphasis on food safety and the identification of contamination risks. SDG 3, promoting good health and wellbeing, is supported by efforts to prevent both acute and chronic health issues arising from heavy metal exposure. The study contributes to SDG 6 on clean water and sanitation by highlighting how contaminated irrigation water can affect food safety. Furthermore, it supports SDG 12 on responsible consumption and production by encouraging safer agricultural practices, including judicious use of fertilizers and pesticides. SDG 13 on climate action is relevant because climate change can influence heavy metal bioavailability in soils, and SDG 15 on life on land is addressed through the promotion of sustainable land use practices that minimize soil contamination.

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Despite the growing research knowledge on heavy metals contamination in food crops globally, there remains a significant knowledge gap regarding the levels and distribution of these contaminants in Kenyan maize, particularly in specific agricultural regions like Machakos County. Most existing studies have been conducted in other countries, particularly Nigeria and other West African nations [5], leaving East African contexts understudied. Additionally, limited analytical capacity in terms of laboratory infrastructure and sophisticated instrumentation has hindered comprehensive food safety monitoring in Kenya. There is also insufficient public awareness regarding heavy metal contamination risks among farming communities and consumers, which perpetuates unsafe agricultural practices and consumption patterns.

This study aimed to address the safety of maize (Zea mays) for human consumption by assessing the levels of lead, cadmium, zinc, copper and Manganese in three popular maize varieties cultivated in Masii Ward, Machakos County. While SC Duma 43 and SC Sungura 301 are engineered hybrids for rapid maturity and superior drought tolerance 90-100 days for Duma 43, 75-85 days for Sungura 301, traditional landraces like Kamba (Kinyaanya) maize often have different genetic structures that affect their stress response and uptake of soil contaminants. Furthermore, by comparing measured heavy metals levels against Maximum Residue Limits (MRLs) established by WHO, FAO, and KEBS, this study assessed food safety and potential consumer health risks in Masii Ward, Mwala Sub County, Machakos County.

Statement of the Problem

Maize constitutes the primary staple food for the majority of Kenyan households, with particularly high consumption rates in rural and peri-urban communities. However, the potential for heavy metal accumulation in maize grains from contaminated agricultural soils presents a serious but often overlooked public health threat [1]

In Machakos County, farmers cultivate maize in areas that may be exposed to various sources of heavy metal contamination, including long-term use of synthetic fertilizers, proximity to urban centres with industrial activities, and irrigation with potentially contaminated water sources [6].

Reports of unexplained health problems among local populations have emerged, yet these ailments have not been systematically investigated or linked to specific causal agents [7]. While some preliminary studies have suggested associations between heavy metal-contaminated food consumption and various health conditions, comprehensive research specifically focused on maize from Machakos County has not been conducted. This knowledge gap is particularly concerning given that heavy metals such as lead, cadmium, copper, zinc, and manganese can cause devastating health effects ranging from neurological damage and developmental delays in children to cardiovascular disease, kidney failure, and cancer in adults.

The situation is further complicated by the fact that different maize varieties may accumulate heavy metals at different rates, meaning that some commonly planted hybrids or traditional varieties could pose greater risks than others [7]. Without adequate data on heavy metal levels in locally consumed maize varieties, it is impossible to make informed decisions about food safety, implement appropriate interventions, or provide evidence-based guidance to farming communities. There is therefore an urgent need to conduct detailed assessments of heavy metal contamination in maize seeds from Machakos County to protect public health and inform agricultural and food safety policies.

General Objective

The general objective of this study was to determine the levels of heavy metals in SC Duma 43, SC Sungura 301 hybrid, and Indigenous Kamba (Kinyaanya) maize seeds from farms in Masii Ward, Mwala Sub-County, Machakos County, Kenya.

Specific Objectives

The specific objectives of this study were to:

1. Determine the levels of lead, cadmium, zinc, copper, and manganese in SC Duma 43, SC Sungura 301 hybrid, and Indigenous Kamba (Kinyaanya) maize seeds from selected farms in Masii Ward, Machakos County.
2. Compare the heavy metal levels in the three different maize seed varieties to identify varietal differences in metal accumulation.
3. Evaluate the potential health risks associated with consumption of the analysed maize varieties based on their heavy metal content.

Justification and Significance of the Study

This study addressed a critical knowledge gap regarding food safety and heavy metal contamination in one of Kenya's most important maize-producing regions. The findings provided essential baseline data on the levels of toxic heavy metals in commonly consumed maize varieties, information that is currently lacking for Machakos County and similar agricultural areas in Kenya. By analysing both modern hybrid varieties and traditional indigenous maize grains, the study offered insights relevant to diverse farming communities with different varietal preferences.

The research has significant implications for public health protection in Masii Ward and the broader Machakos County region. By identifying maize varieties with excessive heavy metal levels, the study enables targeted interventions and informed decision-making for consumers, farmers, and health authorities [8]. The comparison with international and national safety standards provides a clear framework for assessing food safety risks and determining which maize varieties may pose health hazards.

From a policy perspective, this study generated evidence to informal agricultural extension services, food safety regulations, and public health campaigns by guiding recommendation on safe farming practices, fertilizer application, and water quality management to reduce heavy metal accumulation. Additionally, these findings support broader initiative for food safety and nutritional security that align with Kenya's national development agenda and international sustainable goals.

This study contributed to analytical chemistry through an optimized acid digestion protocol suitable for future monitoring programs. Furthermore, using Atomic Absorption Spectroscopy for heavy metal analysis in maize strengthens local expertise and serves as a framework for similar investigation elsewhere.

Finally, the study serves an important educational function by raising awareness among farming communities about heavy metal contamination risks. By sharing findings with local stakeholders, the research will empower communities to make informed choices about crop production and development in Machakos County. Comparing these distinct genetic backgrounds (improved drought-tolerant hybrids versus locally adapted indigenous varieties) is critical for identifying which varieties can be grown in areas without exceeding heavy metal safety standards in produced maize grains.

MATERIALS AND METHODS

Study Area

The research was conducted in Masii Location in Mwala Sub-County, Machakos County, Kenya (Figure1). Machakos County is located in the Eastern region of Kenya, approximately 64 kilometres southeast of Nairobi, the capital city of Kenya. The county lies within the semi-arid to arid agro-ecological zones, characterized by erratic rainfall patterns and generally challenging conditions for rain-fed agriculture. Despite these environmental constraints, the region supports substantial maize production, with farmers relying on this crop as both a staple food and a source of income [9].

The study area is approximately 9 kilometres and covers a catchment area of 72 km^2. Geographically, the location falls between longitude 37.3912° to 37.5496° East and latitude 1.4767° to 1.4104° South. The topography is characterized by gently rolling hills and valleys typical of the Eastern Highlands, with elevation varying across

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the study sites. This variation in altitude influences local microclimates and agricultural practices, with farmers adapting their crop management strategies to local conditions [9].

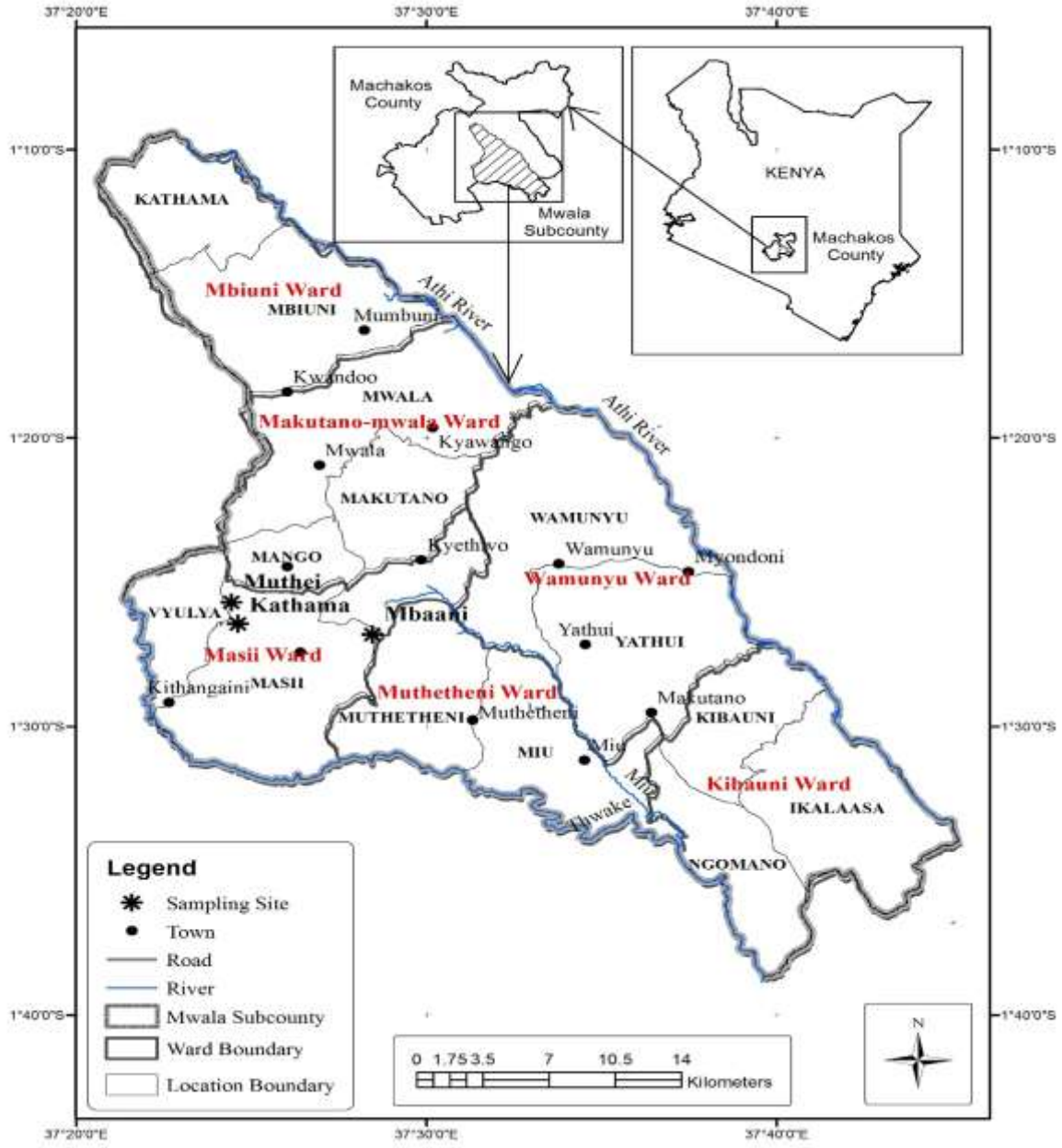


Figure 1: Map of Mwala Sub-County Showing Sampling Sites in Masii Ward

Climate Conditions and Economic Activities in the study area

The climate across all three sites is classified as semi-arid, with mean annual rainfall ranging between 600 - 900 mm, distributed in a bimodal pattern. The long rains typically occur from March to May, while short rains fall between October and December. Temperatures are moderate, with mean annual temperatures ranging from 18°C -26°C. These climatic conditions, combined with the soil characteristics and topography, create an environment where maize production requires careful management and is often supplemented with supplementary irrigation during dry seasons [9].

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Human activities in the study area that could potentially influence heavy metal levels in agricultural soils include intensive farming with regular application of agrochemicals, small-scale commercial activities, transport-related emissions from the roads connecting rural areas to market centres, and in some areas, use of wastewater or water from potentially contaminated sources for irrigation during dry seasons. The area also experiences population pressure, leading to continuous cultivation with minimal fallow periods, which may affect soil health and contaminant dynamics. Income-generating activities in Masii Location include smallholder agriculture focused on maize, beans, and horticultural crops, livestock rearing including cattle, goats, sheep, and poultry, trade and commerce cantered around local markets, and transport services connecting rural communities to urban centres. These economic activities influence agricultural practices and may contribute to environmental contamination through various pathways

Equipment and Apparatus

The analytical work required a comprehensive array of laboratory equipment and apparatus to ensure accurate and reliable results. The primary analytical instrument was an Atomic Absorption Spectrophotometer (AAS), which served as the core tool for heavy metal quantification. This sophisticated instrument was equipped with appropriate hollow cathode lamps for each element of interest and was capable of both flame and graphite furnace atomization, though flame atomization was primarily utilized in this study.

Sample preparation and processing utilized an analytical weighing balance with precision to four decimal places, ensuring accurate measurement of sample masses and reagent volumes. A mortar and pestle made of porcelain was employed for grinding dried maize samples to fine powder, facilitating complete digestion. A hot plate with temperature control capability up to 200°C provided the heat source for acid digestion of samples. Freezer, A muffle furnace, though primarily kept as backup, was available for alternative sample preparation methods if needed.

Glassware employed in the study included 100 mL conical flasks for sample digestion, volumetric flasks of various sizes (25 mL, 50 mL, and 100 mL) for preparation of standard solutions and dilution of digested samples, measuring cylinders of 10 mL and 50 mL capacity for reagent measurements, filter funnels with appropriate diameter to accommodate filter papers, wash bottles for dispensing distilled water, and glass stirring rods for mixing solutions.

Additional equipment included a polyurethane cooler box for sample transportation and temporary storage, maintaining samples at appropriate temperatures during transit from the field to the laboratory. Khaki paper bags, which are breathable and prevent moisture accumulation, were used for collecting and packaging individual samples. A permanent marker pen was essential for labelling samples and containers. Spatulas made of stainless steel or porcelain facilitated transfer of ground samples. Filter papers of appropriate pore size (Whatman Grade 1 or equivalent) were used for filtration of digested samples. Bumping chips or boiling stones were added to digestion flasks to promote smooth boiling and prevent violent bumping during heating. Cork stoppers or appropriate closures were used to seal containers and prevent contamination or evaporation.

All glassware was thoroughly cleaned before use following a rigorous protocol. Items were first washed with laboratory detergent and tap water, then rinsed multiple times with distilled water. For heavy metal analysis, additional cleaning involved soaking glassware in 10% nitric acid for at least 24 hours, followed by thorough rinsing with distilled water. This acid wash step was critical for removing any residual metal contamination that could interfere with trace metal analysis. Glassware was air-dried in a dust-free environment or in a drying oven before use.

Chemicals and Reagents

All chemicals and reagents used in this study were of analytical grade to ensure high purity and minimize contamination. Concentrated nitric acid (HNO_3, 65-70% purity) served as the primary digestion acid, selected for its strong oxidizing properties and ability to dissolve organic matter and release bound metals. Perchloric

acid ($HClO_4$, 70% purity) was included in the digestion mixture to enhance breakdown of resistant organic compounds and ensure complete sample dissolution. Hydrogen peroxide (H_2O_2, 30% purity) acted as an additional oxidizing agent, facilitating digestion of organic materials and helping to achieve clear, colourless digestates.

Distilled deionized water, with conductivity less than 2 µS/cm, was used throughout the study for preparation of solutions, dilutions, rinsing, and as a blank in analytical measurements. The use of high-purity water was essential to avoid introducing metallic contaminants from the water itself.

Standard stock solutions of the target heavy metals and reagents used were obtained from BDH Laboratory reagents Poole England Ltd and were certified reference materials with known concentrations and traceability to international standards. Individual standard solutions were available for lead (Pb), cadmium (Cd), zinc (Zn), copper (Cu), and manganese (Mn), typically at concentrations of 1000 mg/L (1000 ppm). From these stock solutions, working standard solutions at appropriate concentration ranges were prepared by serial dilution using volumetric glassware and acidified distilled deionized water (typically 2% HNO_3) to prevent metal adsorption onto container walls and precipitation.

Dilute nitric acid solutions at various concentrations (2%, 5%, and 10%) were prepared from the concentrated acid for different purposes including cleaning glassware, acidifying solutions, and preparing blanks and standards. All reagent bottles were clearly labelled with content information, concentration, preparation date, and expiry date where applicable. Reagents were stored according to manufacturer recommendations, with acids kept in designated acid storage cabinets in well-ventilated areas.

Sites selection and Atherogenic Activities around the sampling site

Three selected sampling sites in Mbaani, Kathama, and Muthei sub-locations in Masii Ward, Mwala Sub-County (Figure 1) were selected. These sites were chosen based on several criteria including active maize cultivation, accessibility for sample collection, representation of typical farming systems in the area, and willingness of farmers to participate in this study. The Mbaani site is located at latitude -1.45196° and longitude 37.48384°, with an elevation of approximately 1200 meters above sea level (Table 1). This area is characterized primarily by agricultural activities, with maize being a dominant crop alongside beans, pigeon peas, and vegetables [9]. The soils in Mbaani are predominantly reddish-brown, suggesting weathered volcanic parent material, and farmers typically apply both organic manures and synthetic fertilizers to maintain soil fertility. The Kathama sampling site, is positioned at latitude -1.44074° and longitude 37.41032°, sits at an elevation of approximately 1190 meters above sea level. This ward exhibits more diverse economic activities compared to Mbaani, with trade and commerce playing significant roles alongside agriculture. The proximity to local markets and trading centres means that agricultural inputs including fertilizers and pesticides are readily accessible to farmers. The area experiences moderate human activity and vehicle traffic, which could potentially contribute to atmospheric deposition of certain contaminants. Muthei ward, the third sampling location, is found at latitude -1.43958° and longitude 37.4078°, with a lower elevation of approximately 1011 meters above sea level (Table 1). This site is characterized by mixed farming systems with particular emphasis on livestock management alongside crop production. The integration of livestock activities means that animal manures are commonly used as soil amendments, and the area maintains higher organic matter inputs compared to areas relying solely on synthetic fertilizers. The lower elevation also results in slightly warmer conditions and potentially different cropping patterns [9].

Table 1: Selected Sampling Sites in Masii Ward and Atherogenic activities around the site

S/No	Site Name	Latitude	Longitude	Hight above sea levels (m)	Human Activities
1	Mbaani	-1.45196	37.48384	1200	Maize, kales, beans, Fruits

2	Kathama	-1.44074	37.41032	1190	Maize, Fruits, Trade and commercial activities
3	Muthei	-1.43958	37.4078	1011	Maize, livestock managements

Sample Collection, Transportation to the laboratory, Storage, and Preparation

Sample collection was conducted during the harvest season in March 2024 when maize had reached physiological maturity, fresh and dry grains cobs were collected. The timing of collection was important to ensure that samples represented the actual product consumed by local populations. Three different maize varieties were targeted: SC Duma 43 hybrid, SC Sungura 301 hybrid, and Indigenous Kamba maize (locally known as Kinyaanya). These varieties represent the range of maize types commonly grown in Masii Ward, with the two genetically improved drought-tolerant hybrids varieties promoted through agricultural extension services, while the indigenous variety represents traditional germplasm maintained by farmers over generations.

Samples were collected from three separate farms located in Mbaani, Kathama, and Muthei sub-locations in Masii Ward (Figure 1). At each farm, both fresh maize (just harvested with higher moisture content) and dry maize (harvested field dried) were collected to provide a comprehensive assessment. A random sampling approach was employed to ensure representative samples and minimize selection bias. From each farm (Figure 2), maize was collected from different parts of the field rather than from a single location, and multiple cobs were combined to create a composite sample representing that farm.



Figure 2: Maize seeds samples collection from Mbaani sampling site

Each sample, consisting of approximately one kilogram of maize kernels (Figure 3), was carefully packed in clean khaki paper bags. Khaki bags were chosen because they are breathable, preventing moisture accumulation

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that could promote mold growth, while also being strong enough to prevent spillage during transportation. Each sample bag was clearly labelled with detailed information including sample identification code, variety name, collection site, collection date, and whether the sample was fresh or dry. The labelling system ensured proper tracking throughout the analytical process.

The labelled samples were each placed in a clean polyurethane cooler box for transportation to the Department of Chemistry laboratory, University of Nairobi for storage an analysis. While refrigeration was not strictly necessary for dry grain samples, the cooler box provided protection from temperature extremes, physical damage, and contamination during the approximately two-hour journey from Masii Location to the Department of Chemistry laboratory. Upon arrival at the laboratory, samples were transferred to the Inorganic Chemistry Laboratory where they were stored in airtight containers at room temperature in a dry, well-ventilated area until analysis the following day.



Figure 3: Maize seeds samples collected for analysis from Mbaani Site

In the laboratory, preparation began with drying fresh samples to remove excess moisture, which could interfere with accurate weighing and subsequent digestion. Samples were spread in thin layers on clean aluminium foil and placed in a drying oven set at 60°C for 24-48 hours, with the exact duration depending on initial moisture content. The field dried maize samples were also further dried at 60°C for 4 hours. This temperature was selected to efficiently remove water without causing thermal degradation of the grain matrix or potential volatilization of certain metal species. Samples were considered sufficiently dry when consecutive weighing showed less than 0.1% weight change, indicating stable moisture content.

Once dried, samples were ground to fine powder using a clean porcelain mortar and pestle. The grinding process was conducted systematically, with thorough cleaning of the mortar and pestle between different samples using distilled deionized water and ethanol, followed by air drying. This prevented cross-contamination between samples. The ground material was passed through a fine mesh sieve to ensure particle size uniformity, with the aim of achieving particles smaller than 0.5 mm in diameter. Fine particle size is crucial for efficient acid digestion as it increases the surface area available for acid attack and ensures homogeneity of the sample.

The ground and sieved samples were stored in clean, labelled plastic containers with tight-fitting lids. The containers were kept in a desiccator when not in use to prevent moisture absorption from the atmosphere, which

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could alter sample weight and introduce potential contamination. Prior to digestion, samples were allowed to equilibrate to room temperature while still in sealed containers.

Sample Digestion Protocol

The digestion of maize samples constitutes a critical step in heavy metal analysis, as it must completely break down the organic matrix and release all metals into solution without losses due to volatilization or incomplete dissolution. For this study, a novel optimized digestion method was developed through preliminary trials, resulting in an efficient protocol that minimized reagent consumption, reduced digestion time, and simplified the overall procedure while maintaining excellent recovery rates.

The optimized digestion mixture consisted of nitric acid, perchloric acid, and hydrogen peroxide in a volume ratio of 2.5:0.75:0.5. This specific combination was selected based on preliminary experiments that tested various acid ratios and evaluated their effectiveness in achieving complete digestion while producing clear, colourless digestates suitable for AAS analysis. The synergistic action of these three oxidizing agents ensured thorough breakdown of complex organic compounds present in maize kernels, including proteins, lipids, and carbohydrates.

For each sample, 2.0 g of the ground, dried maize powder was accurately weighed using the analytical balance and transferred into a clean 100 mL conical flask. The samples were analysed in triplicate, meaning three separate 2.0 g portions were weighed from each sample to provide statistical reliability and allow calculation of mean values and standard deviations. The conical flask shape was preferred for digestion as it allows for refluxing of acid vapours and minimizes sample loss during heating.

To each flask containing 2.0 g of sample, the acid mixture was added. Specifically, 2.5 mL of concentrated nitric acid was added first, followed by 0.75 mL of perchloric acid, and finally 0.5 mL of hydrogen peroxide. The acids volumes were dispensed using calibrated pipettes or micropipettes for accuracy. After addition of the acid mixture, the flasks were gently swirled to ensure the sample was thoroughly wetted and mixed with the acids. The flasks were then allowed to stand at room temperature for approximately 30 minutes to permit initial pre-digestion reactions to occur, which helps prevent violent reactions when heating begins.

Following the pre-digestion period, the flasks were placed on a hot plate in a fume hood. The fume hood was essential for safety, as the digestion process releases nitrogen oxides and other potentially harmful fumes. The hot plate temperature was set to 105°C, a temperature selected through optimization studies as providing efficient digestion without excessive loss of acids through evaporation. The samples were heated at this temperature for 2 hours and 30 minutes, with occasional gentle swirling to ensure uniform heating and mixing.

During the digestion process, the initially thick, yellow-brown mixture gradually became clearer as organic matter was oxidized and dissolved. The endpoint of successful digestion was indicated by the formation of a clear, colourless or very pale-yellow solution with no visible particulate matter. If any sample remained turbid or showed brownish coloration after the prescribed digestion time, heating was continued for an additional 30 minutes. However, with the optimized protocol, most samples achieved complete digestion within the standard 2.5-hour period.

After digestion was complete, the flasks were removed from the hot plate and allowed to cool to room temperature. Cooling was important before filtration to prevent thermal stress on filter papers and to allow any fumes to dissipate. The cooled digestates were filtered through Whatman Grade 1 filter paper (or equivalent) placed in glass funnels. The filtration step removed any undissolved residue, though with complete digestion, minimal residue should remain.

The clear filtrate was collected in clean volumetric flasks and diluted to a final volume of 50 mL using distilled deionized water. This dilution served multiple purposes including reducing acid concentration to levels compatible with the AAS instrument, bringing metal concentrations into the optimal measurement range of the

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instrument, and providing sufficient volume for replicate analysis if needed. The diluted digestates were transferred to clean plastic bottles and labelled with sample identification, digestion date, and any dilution factors a

The efficiency and reliability of the digestion protocol were validated through spike-recovery experiments. In these validation studies, known quantities of metal standards were added to portions of sample matrix, and the samples were digested and analysed following the standard protocol. The measured levels were compared to expected values based on the added spike amounts. Recovery percentages, calculated as (measured concentration/expected concentration) × 100, ranged between 94 % and 110 % for all five target metals. These recovery values fall within the acceptable range of 85-115 % typically required for trace metal analysis, confirming that the digestion method effectively released metals from the sample matrix without significant losses or contamination.

Heavy Metal Analysis Using Atomic Absorption Spectroscopy

Following digestion and dilution processes, samples were analysed using Atomic Absorption Spectroscopy to quantify the concentrations of lead, cadmium, zinc, copper, and manganese. The analysis was performed on a flame atomic absorption spectrophotometer equipped with appropriate hollow cathode lamps for each element and using an air-acetylene flame for atomization.

Prior to sample analysis, the AAS instrument was calibrated using standard solutions prepared from certified reference materials. For each element, a series of standard solutions at different concentrations were prepared by serial dilution of stock standard solutions. The concentration ranges were selected to bracket the expected levels in samples and to span the linear response range of the instrument. Specifically, zinc standards were prepared at concentrations of 0, 2, 4, 6, 8, and 10 mg/L. Cadmium standards covered 0, 5, 10, 15, and 20 mg/L. Copper standards were at 0, 2, 4, 6, 8, and 10 mg/L. Manganese standards ranged from 0, 5, 10, 15, to 20 mg/L. Lead standards were prepared at 0, 2, 4, 6, and 8 mg/L.

The zero concentration standard served as the blank and was prepared using the same acid matrix as the samples (typically 5% nitric acid) to match matrix composition and minimize interference effects. All standards were prepared fresh daily for analysis or stored at 4°C for no more than one week to prevent degradation or adsorption losses.

Calibration curves were constructed by measuring the absorbance of each standard solution at the element-specific wavelength (Table 2) and plotting absorbance versus concentration. The wavelengths used for analysis were optimized for maximum sensitivity and were as follows: zinc at 213.9 nm, cadmium at 228.8 nm, copper at 324.8 nm, manganese at 279.5 nm, and lead at 217.0 nm [10]. These wavelengths correspond to the most sensitive absorption lines for each element and are standard analytical wavelengths used in atomic absorption spectroscopy.

Table 1: The Optimum conditions for AAS operation

Metal ion	Wavelength
Zn	217.0005
Cd	357.8687
Cu	324.7540
Mn	232.0030
Pb	217.0005

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The flame composition and flow rates were optimized for each element to achieve maximum absorbance signal and stability. For most elements, an air-acetylene flame was used with fuel-lean (oxidizing) conditions. The burner height was adjusted to position the optical beam through the optimal part of the flame where the population of free ground-state atoms is maximized.

For each calibration standard, the solution was aspirated into the flame through the nebulizer system, which converts the liquid into a fine aerosol. The instrument measured the absorbance and the data were recorded. Linear regression analysis was performed to determine the calibration equation relating absorbance to concentration. The quality of the calibration was assessed using the correlation coefficient (R^2), with values above 0.99 considered acceptable for quantitative analysis.

Following calibration, the digested sample solutions were analysed in the same manner. Each sample was run in triplicate by aspirating the solution three times and recording the average absorbance. Between samples, the nebulizer system was rinsed with dilute nitric acid and distilled water to prevent carryover contamination. Blank solutions (acid matrix without sample) were run periodically to monitor baseline stability and check for instrumental drift.

The instrument's software automatically calculated sample concentrations based on the calibration curves. However, these concentrations represented the levels in the diluted digestate and required correction for dilution factors to determine the actual concentration in the original dry sample. The calculation accounted for the mass of sample digested, the final volume of digestate, and any additional dilutions performed.

Quality control measures implemented during analysis included running certified reference materials when available, analysing blank samples to check for contamination, running duplicate samples to assess precision, conducting spike recovery tests by adding known amounts of metals to selected samples and measuring recovery, and periodically re-calibrating the instrument during extended analysis sessions to compensate for any instrumental drift.

The limits of detection (LOD) for each metal element was determined as three times the standard deviation of ten replicate measurements of the blank, divided by the slope of the calibration curve. The limits of quantification (LOQ) were calculated as ten times the standard deviation of the blank divided by the slope. These parameters provide information about the lowest concentrations that can be reliably detected and quantified by the analytical method.

Data Analysis and Statistical Treatment

All measurements were performed in triplicate to ensure reliability and allow statistical evaluation of results. The triplicate values for each sample were examined for outliers using appropriate statistical tests, though in general, values that differed from the mean by more than three standard deviations were flagged for investigation.

Results for heavy metal concentrations were expressed as mean ± standard deviation, calculated using Microsoft Excel. The standard deviation provides a measure of the precision of the measurements, with smaller values indicating better reproducibility. Data were organized in tables showing concentrations for each metal in each variety from each sampling location.

Graphical presentations were prepared using Excel software to facilitate visual comparison of metal levels across varieties and against regulatory limits. Bar charts with error bars representing standard deviations were created to show mean concentrations. These visualizations help identify patterns and differences that may not be immediately apparent from tabular data alone.

Comparison with regulatory limits established by the World Health Organization (WHO)/Food and Agriculture Organization (WHO/FAO), and Kenya Bureau of Standards (KEBS) allowed assessment of food safety status. Samples with concentrations exceeding maximum permissible limits were flagged as potential health risks.

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RESULTS AND DISCUSSION

Calibration Curves Preparation and Analytical Performance

The reliability and accuracy of heavy metal determinations by atomic absorption spectroscopy depend fundamentally on the quality of calibration curves generated from standard solutions. In this study, calibration curves were prepared for each of the five target metals using freshly prepared standard solutions at multiple concentration levels. The calibration data, regression equations, and correlation coefficients provide important information about the analytical method's performance and the relationship between absorbance and concentration.

Heavy Metal levels in Maize Varieties

The analysis of heavy metals in the three maize varieties from Masii ward revealed significant contamination, particularly with lead and cadmium, while zinc, copper, and manganese were present at lower levels. Table 3 presents a comprehensive summary of the measured levels for all five heavy metals in each variety, along with the regulatory limits established by WHO/FAO, KEBS and the analytical limits of detection (LOD).

Table 3: Heavy metal levels (mg/g) in three maize seeds varieties and the recommended values

Maize Variety	Zn	Cd	Cu	Mn	Pb
SC Sungura 301	0.343 ± 0.0505	1.998 ± 0.11	0.756 ± 0.101	2.745 ± 0.851	8.990 ± 0.752
SC Duma 43	0.389 ±0.0007	0.562 ± 0.217	0.741 ± 0.0741	1.748 ± 0.110	10.449 ± 0.398
Indigenous Kamba Maize	0.372 ± 0.0257	1.843 ± 0.373	0.700± 0.0380	0.270 ± 0.0586	8.247± 0.798
Limits of Detection	0.05	0.05	0.01	0.02	0.01
Recommended levels					
WHO	30-95	0.1	10 - 50	5 -20	0.2
FAO	38	0.1	0.05-0.5	5 - 20	0.2
KEBS	33-65	0.1	10-50	5- 20	0.2

Source: [11, 12]

Among the three varieties studied, SC Duma 43 hybrid generally exhibited the highest levels of heavy metal contamination, followed by the indigenous Kamba maize, with SC Sungura 301 showing somewhat lower but still concerning levels for certain metals (Table 3). This pattern was not consistent across all metals, however, as different varieties showed variable accumulation for different metals, reflecting the complex interactions between plant genetics, metal uptake mechanisms, and environmental factors.

The overall pattern of heavy metal abundance in the maize samples followed the order: Lead >> Cadmium > Manganese > Copper ≈ Zinc. This distribution indicates that lead contamination was the most severe problem, with levels far exceeding all other metals. Cadmium, while lower than lead, still reached alarmingly high levels well above safety limits of 0.1 mg/g by [11, 12]. The essential micronutrients zinc, copper, and manganese were present at much lower levels, generally below recommended nutritional levels.

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Zinc Levels in Maize Varieties

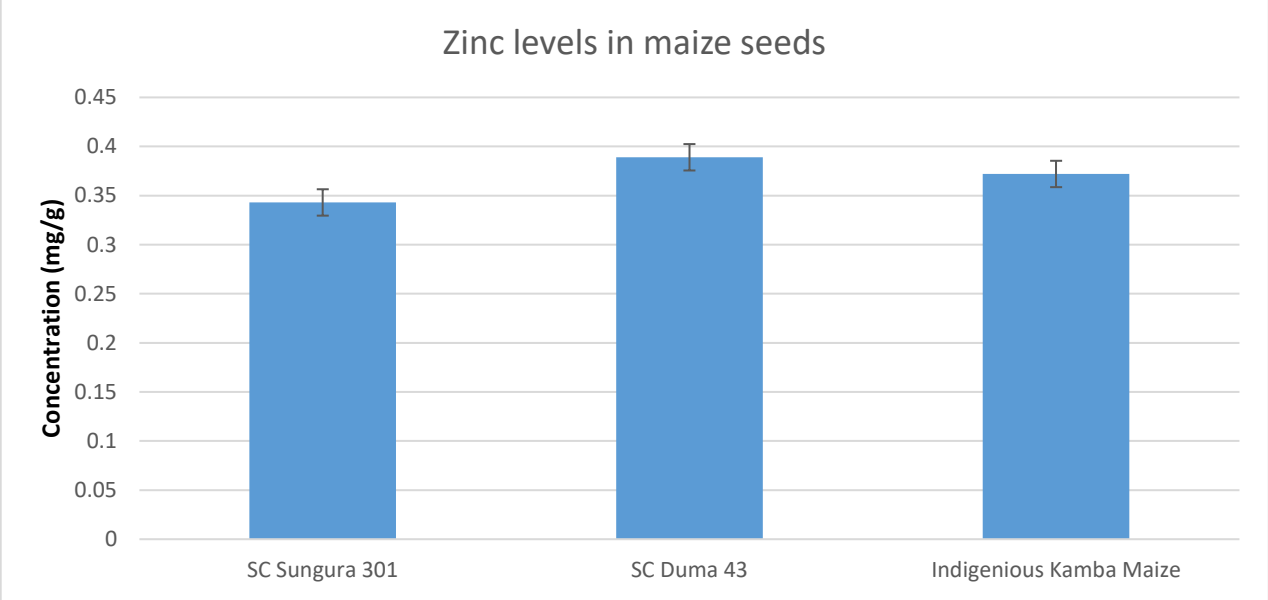


Figure 4: Zinc levels in SC Sungura 301, SC Duma 43 and the Indigenous Kamba maize seeds

Zinc concentrations in the three maize varieties were relatively uniform and low. SC Sungura 301 contained 0.343 ± 0.0505 mg/g zinc, SC Duma 43 had 0.389 ± 0.0007 mg/g, and the indigenous Kamba maize showed 0.372 ± 0.0257 mg/g. Among the three varieties, SC Duma 43 hybrid exhibited the highest zinc content, though the difference from the other varieties was small and may not be biologically significant. SC Sungura 301 had the lowest zinc level, while the indigenous variety fell between the two hybrids (Figure 4).

All three zinc levels were dramatically below the recommended levels of 30-95 mg/g established by WHO, FAO, and KEBS for adequate nutritional content in cereal grains. This severe zinc deficiency in the maize samples raises important concerns from a nutritional standpoint. Zinc is an essential micronutrient required for numerous physiological functions including immune system function, wound healing, protein synthesis, DNA synthesis, and cell division. Adequate zinc intake is particularly crucial for children's growth and development, pregnant and lactating women, and for maintaining general health in all age groups.

The low zinc levels found in these maize varieties suggest that communities relying heavily on maize as their staple food may be at risk of zinc deficiency. Dietary zinc deficiency manifests as impaired immune function leading to increased susceptibility to infections, delayed wound healing, loss of appetite, growth retardation in children, hair loss, diarrhoea, and mental lethargy. In severe cases, particularly in young children, zinc deficiency can contribute to stunting and increased mortality from infectious diseases.

The reasons for low zinc content in these maize samples are likely multifactorial. Soil zinc deficiency is common in many Kenyan agricultural areas, particularly in soils with high pH, low organic matter content, or high phosphorus levels which can interfere with zinc availability. Additionally, the maize varieties themselves may not be efficient at zinc uptake or translocation to grains. Plant breeding efforts in recent decades have focused primarily on yield improvement rather than nutritional quality, potentially leading to reduced micronutrient density in modern cultivars.

While the immediate health concern in this study relates to toxic metal contamination, the zinc deficiency represents a chronic nutritional problem that undermines health and wellbeing over the long term. Biofortification strategies, including development of zinc-enriched maize varieties through conventional breeding or agronomic interventions such as zinc fertilization, may be necessary to address this nutritional gap [13].

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It is worth noting that while the measured zinc levels are far below recommended nutritional levels, they are also well below levels that would cause toxicity. Zinc toxicity typically becomes a concern only at levels exceeding 100 mg/g, far above what was detected in these samples. Therefore, from a food safety perspective regarding zinc toxicity, these maize varieties pose no risk. However, the severe nutritional deficiency remains a significant public health concern that warrants attention through agricultural and nutritional interventions.

Cadmium Levels in Maize Varieties

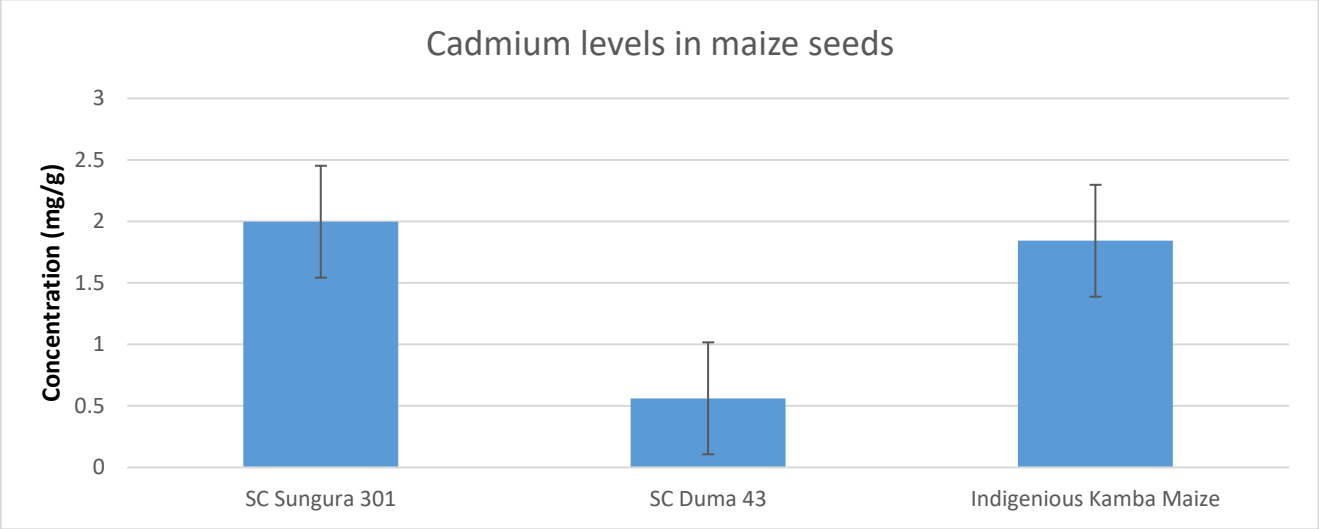


Figure 5**:** Cadmium levels in SC Sungura 301, SC Duma 43 and the Indigenous Kamba maize

Cadmium levels in the three maize varieties presented the first major food safety concern identified in this study. The concentrations measured were 1.998 ± 0.110 mg/g in SC Sungura 301, 0.562 ± 0.217 mg/g in SC Duma 43, and 1.843 ± 0.373 mg/g in the indigenous Kamba maize (Table 3). These values far exceeded the maximum permissible limits of 0.1-0.5 mg/g established by WHO, FAO, and KEBS for cadmium in food grains. SC Sungura 301 showed the highest cadmium contamination, approximately four to twenty times higher than the upper safety limit, depending on which regulatory threshold is applied. The indigenous Kamba variety exhibited similarly elevated levels at 1.843 mg/g, while SC Duma 43 showed the lowest contamination among the three varieties, though still exceeding the safety limits (Figure 5).

The presence of cadmium at these elevated levels renders all three maize varieties unsafe for human consumption according to international food safety standards. Cadmium is classified as a Group 1 human carcinogen by the International Agency for Research on Cancer, with well-documented evidence of its carcinogenic potential. The metal accumulates primarily in kidneys and liver, where it has an extremely long biological half-life ranging from 10 to 30 years. This means that even relatively low daily intakes can lead to progressive accumulation over a lifetime, eventually reaching toxic levels [14].

The health consequences of chronic cadmium exposure through dietary intake are severe and multisystemic. Kidney damage represents the most characteristic and sensitive endpoint of cadmium toxicity [4]. The metal specifically targets the proximal tubules of the nephron, causing tubular dysfunction that manifests initially as low-molecular-weight proteinuria [7]. As exposure continues and cadmium accumulates, more severe nephrotoxicity develops, including generalized proximal tubular dysfunction known as Fanconi syndrome. This condition is characterized by excessive urinary losses of glucose, phosphate, amino acids, and other substances that should be reabsorbed by healthy kidneys. The urinary losses of calcium and phosphate contribute to the skeletal manifestations of cadmium poisoning.

Cadmium-induced bone disease can present as osteomalacia, osteoporosis, and in severe cases, the extremely painful condition known as itai-itai disease, which was first identified in Japan among populations exposed to

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high cadmium levels through contaminated rice consumption [13]. The disease causes severe bone pain, fractures, and skeletal deformities due to cadmium's interference with vitamin D metabolism and calcium-phosphate homeostasis, combined with direct toxic effects on bone cells.

Beyond kidney and bone effects, cadmium damages the liver, causing hepatocellular injury, elevated liver enzymes, and potentially fibrosis with prolonged exposure. The metal generates oxidative stress by depleting cellular antioxidant defences, particularly glutathione, and promoting formation of reactive oxygen species. This oxidative damage affects multiple cellular components including lipids, proteins, and DNA. Cadmium's neurotoxic properties affect both central and peripheral nervous systems, causing olfactory dysfunction, learning disabilities, behavioural changes, and motor impairment [14].

The high cadmium levels found in these maize varieties are particularly concerning given that maize serves as a staple food consumed daily in large quantities by households in Masii Ward and throughout Machakos County. With typical maize consumption rates in Kenya averaging 200-400 grams per person per day, individuals consuming this contaminated maize would be exposed to cadmium doses far exceeding safe intake levels. The provisional tolerable weekly intake for cadmium, as established by WHO and FAO, is 2.5 micrograms per kilogram body weight. For a 60-kilogram adult, this translates to 150 micrograms per week or approximately 21 micrograms per day. Consumption of just 100 grams of maize containing 1.8 mg/g cadmium would deliver 180 milligrams of cadmium, more than 8,500 times the acceptable daily intake. Even accounting for the fact that bioavailability from food is typically lower than 100%, the exposure levels remain grossly excessive and pose serious health risks.

The sources of cadmium contamination in these maize samples require investigation. Possible pathways include use of phosphate fertilizers contaminated with cadmium, irrigation with contaminated water, atmospheric deposition from industrial sources or waste burning, and natural geological sources if the area has cadmium-rich parent rock. The observation that all three varieties, including both modern hybrids and the traditional indigenous type, show elevated cadmium suggests that the contamination source is environmental rather than variety-specific, though the differences in uptake efficiency between varieties indicate that genetic factors also play a role.

Copper Levels in Maize Varieties

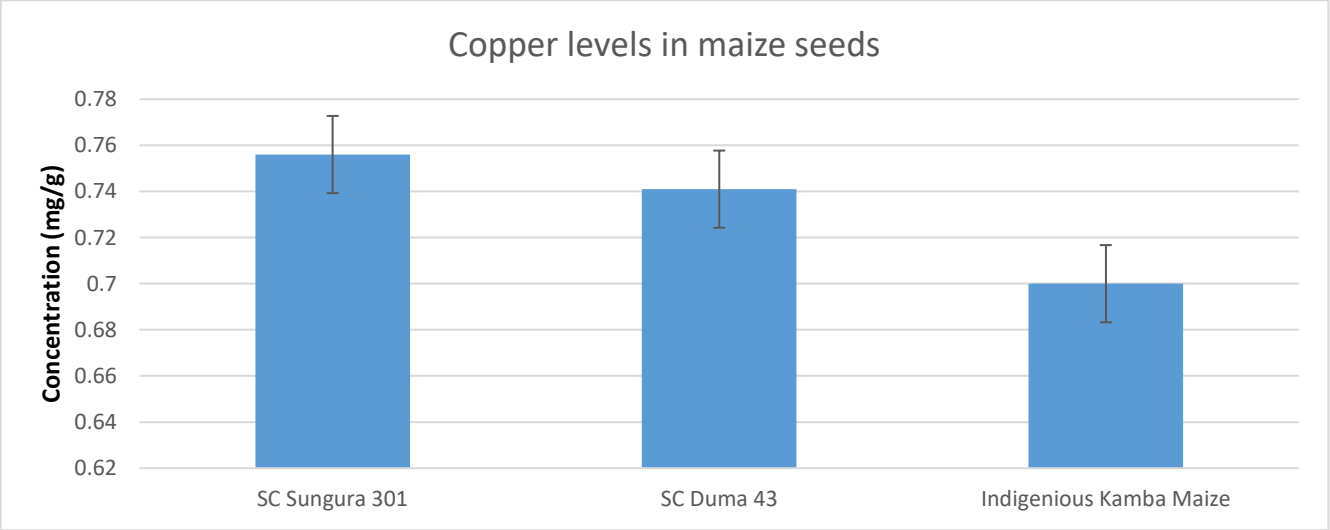


Figure 6 Copper levels in SC Sungura 301, SC Duma 43 and the Indigenous Kamba maize

Copper concentrations in the maize varieties were relatively uniform and low, with SC Sungura 301 containing 0.756 ± 0.101 mg/g, SC Duma 43 showing 0.741 ± 0.0741 mg/g, and the indigenous Kamba maize having 0.700 ± 0.0380 mg/g (Table 3). These values were substantially below the recommended range of 10-50 mg/g established by regulatory authorities for adequate nutritional content in cereal grains. The indigenous Kamba

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variety had the lowest copper content, while SC Sungura 301 exhibited slightly higher levels, though the differences among varieties were small (Figure 6).

From a food safety perspective regarding copper toxicity, these levels pose no concern. Copper toxicity in humans typically requires intake of amounts far exceeding what these maize samples contain. The absence of copper contamination is encouraging, as excessive copper can cause serious health problems including liver damage, gastrointestinal distress, and neurological effects. The levels detected are consistent with normal background copper content in cereals and suggest that agricultural practices in the study area are not introducing problematic copper contamination.

However, similar to the situation with zinc, the low copper levels raise nutritional concerns. Copper is an essential trace element required for numerous physiological functions including iron metabolism and hemoglobin formation, connective tissue formation through lysyl oxidase activity, energy production in mitochondria, neurotransmitter synthesis, immune function, and antioxidant defences through copper-zinc superoxide dismutase. Copper deficiency, while less common than iron or zinc deficiency, can cause anaemia that does not respond to iron supplementation, neutropenia leading to increased infection susceptibility, bone abnormalities including osteoporosis, neurological problems, and cardiovascular issues.

The deficiency in copper, combined with the already noted zinc deficiency, suggests that maize from this region may not provide adequate levels of essential trace minerals. This micronutrient deficiency pattern likely reflects soil nutrient depletion, inadequate fertilization practices focusing primarily on macronutrients like nitrogen and phosphorus while neglecting micronutrients, and possibly selection of high-yielding varieties that have lower mineral density due to dilution effects as more biomass is produced from the same soil mineral supply [14].

Manganese Levels in Maize Varieties

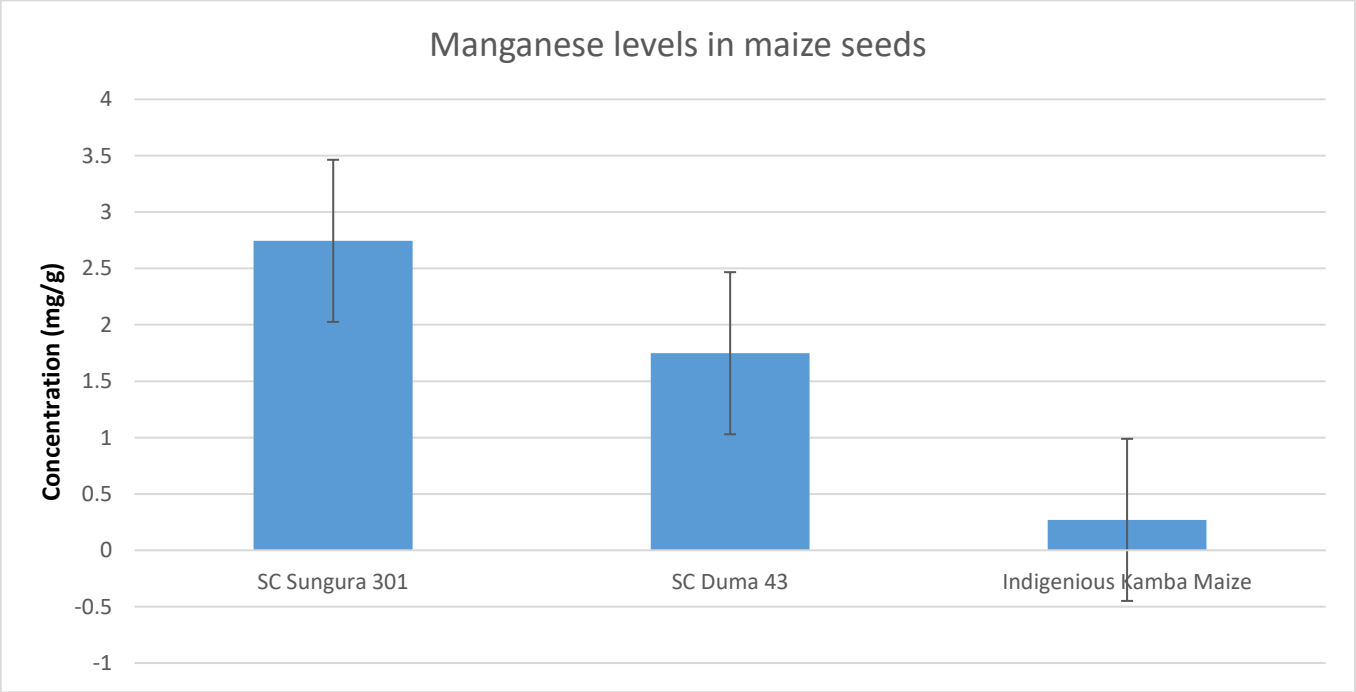


Figure 7**:** Manganese levels in SC Sungura 301, SC Duma 43 and the Indigenous Kamba maize

Manganese concentrations showed considerable variation among the three maize varieties. SC Sungura 301 contained 2.745 ± 0.851 mg/g, SC Duma 43 had 1.748 ± 0.110 mg/g, and the indigenous Kamba maize showed only 0.270 ± 0.0586 mg/g (Table 3). This represents more than a ten-fold difference between the highest and lowest values, indicating substantial varietal differences in manganese accumulation. The indigenous Kamba variety had dramatically lower manganese content compared to both hybrid varieties, while SC Sungura 301 exhibited the highest levels (Figure 7).

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Despite this variability, all three values fell below the recommended range of 5-20 mg/g established by [11, 12] for adequate manganese content in food grains (Table 3). From a toxicity standpoint, none of the samples approached the threshold of concern, as manganese toxicity typically becomes problematic only at levels exceeding 20 mg/g. The absence of manganese contamination is positive from a safety perspective, as excessive manganese intake can cause serious neurological problems including a Parkinson's-like syndrome known as manganism.

The relatively high standard deviation observed for SC Sungura 301 manganese measurements (±0.851) compared to the mean value (2.745) indicates considerable variability among replicate samples. This variability could reflect heterogeneity in the original sample, variations in the growing conditions or soil manganese availability across different parts of the farm, or analytical measurement uncertainty. The coefficient of variation for this measurement is approximately 31%, which is higher than desirable for quantitative analysis and suggests that the manganese results should be interpreted with appropriate caution.

From a nutritional perspective, the low manganese levels, particularly in the indigenous variety, may contribute to dietary inadequacy. Manganese is an essential trace element required for bone formation, amino acid metabolism, cholesterol and carbohydrate metabolism, and functioning as a cofactor for several important enzymes including manganese superoxide dismutase, an antioxidant enzyme [7]. While manganese deficiency in humans is rare due to the widespread occurrence of this element in plant foods, very low dietary intake could theoretically contribute to impaired growth, skeletal abnormalities, altered glucose and lipid metabolism, and increased oxidative stress [15].

The varietal differences in manganese accumulation are noteworthy and suggest that genetic factors influence uptake and translocation of this metal to grains. Modern breeding programs could potentially select for or develop varieties with improved manganese accumulation to enhance nutritional quality, though care must be taken not to select for varieties that also accumulate toxic metals like cadmium or lead more efficiently.

Lead Levels in Maize Varieties

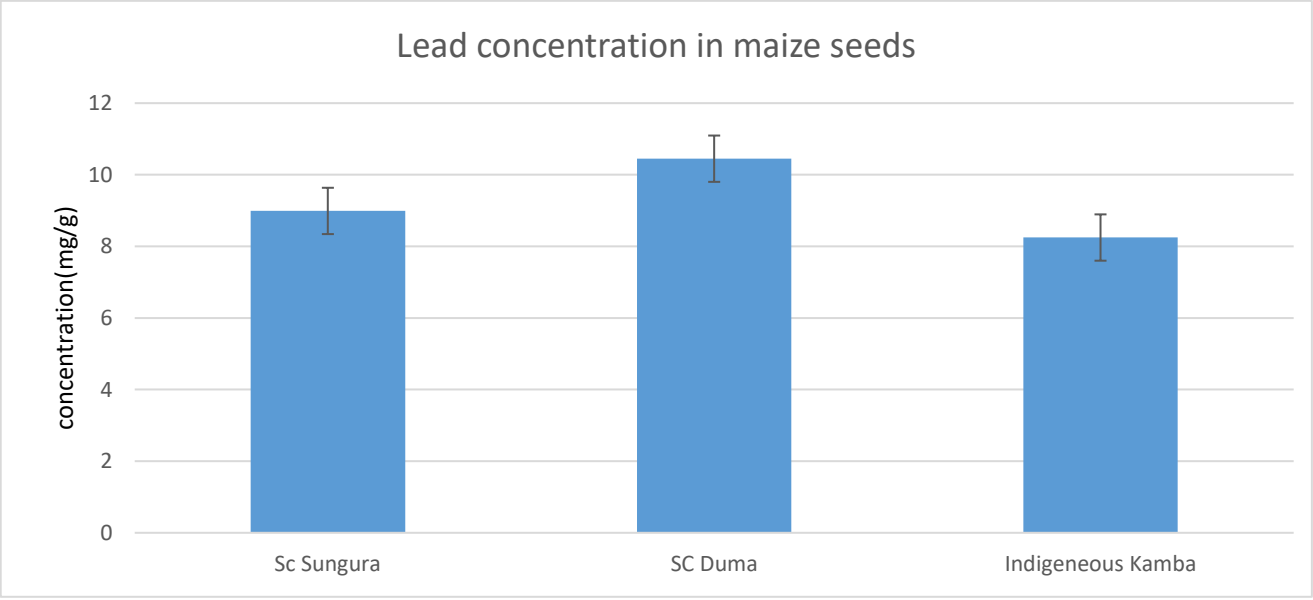


Figure 8: Lead levels in SC Sungura 301, SC Duma 43 and the Indigenous Kamba maize

Lead levels in the maize varieties represented the most severe food safety concern identified in this study. The levels measured were alarmingly high across all three varieties: SC Sungura 301 contained 8.990 ± 0.752 mg/g, SC Duma 43 showed 10.449 ± 0.398 mg/g, and the indigenous Kamba maize had 8.247 ± 0.798 mg/g (Table 3). These levels exceeded the maximum permissible limit of 0.2-0.5 mg/g established by WHO, FAO, and KEBS by factors ranging from approximately 16 to 52 times, depending on which regulatory threshold is applied. SC

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Duma 43 hybrid exhibited the highest lead contamination, followed closely by SC Sungura 301, while the indigenous variety showed slightly lower but still extremely elevated levels (Figure 8).

The presence of lead at these extraordinarily high concentrations renders all three maize varieties completely unsafe for human or animal consumption. Lead is one of the most thoroughly studied environmental toxicants, with no known safe level of exposure. Even very low blood lead levels, once considered acceptable, are now recognized to cause adverse health effects, particularly in children [7]. The levels found in these maize samples would deliver lead doses far exceeding any conceivable safety limit.

Lead exerts toxic effects across virtually every organ system in the body, with the nervous system, kidneys, blood-forming system, and cardiovascular system being particularly vulnerable. In children, lead neurotoxicity causes reduced intelligence quotient, learning disabilities, attention deficit disorders, behavioural problems, and impaired academic performance [15]. These neurodevelopmental effects can occur at blood lead levels once thought to be safe and are largely irreversible even after exposure cessation. Longitudinal studies have demonstrated that childhood lead exposure is associated with reduced educational attainment, lower income in adulthood, and increased risk of criminal behavior.

In adults, lead exposure contributes to hypertension and cardiovascular disease through multiple mechanisms including direct effects on vascular smooth muscle, interference with nitric oxide production, promotion of oxidative stress, and effects on the renin-angiotensin system. Chronic lead exposure is associated with increased risk of heart attack, stroke, and cardiovascular mortality. Lead nephrotoxicity initially presents as proximal tubular dysfunction but with continued exposure progresses to chronic interstitial nephritis, tubular atrophy, and chronic kidney disease that may eventually require dialysis [13].

Lead interferes with heme synthesis, causing anaemia even at relatively low exposure levels. The metal inhibits several enzymes in the heme biosynthetic pathway, particularly aminolaevulinic acid dehydratase and ferro chelatase. This results in accumulation of intermediate compounds and reduced hemoglobin production. Lead also shortens red blood cell lifespan, contributing further to anaemia [14].

The reproductive toxicity of lead affects both males and females. In men, lead exposure reduces sperm count, impairs sperm motility, and alters sperm morphology. In women, lead interferes with normal reproductive function, increases risk of spontaneous abortion and stillbirth, and can cause premature delivery and low birth weight. Lead readily crosses the placenta, exposing the developing foetus to its neurotoxic effects during the critical periods of brain development.

Lead is classified as a probable human carcinogen based on sufficient evidence in animal studies and limited evidence in humans. The metal damages DNA through generation of reactive oxygen species, interferes with DNA repair mechanisms, and disrupts normal cell cycle regulation. These carcinogenic mechanisms contribute to increased cancer risk with chronic exposure [13].

Given typical maize consumption patterns in Kenya, individuals consuming this contaminated maize would be exposed to lead doses posing severe health risks. For a person consuming 300 grams of maize daily with a lead content of 9 mg/g, the daily lead intake would be 2,700 milligrams, an astronomical amount compared to safe intake levels. The provisional tolerable weekly intake for lead, according to WHO, is 25 micrograms per kilogram body weight. For a 60-kilogram adult, this translates to 1,500 micrograms per week or about 214 micrograms per day. The exposure from contaminated maize would exceed this by more than 12,000-fold. Even children consuming smaller portions would receive lead doses causing serious health consequences.

The sources of such extreme lead contamination require urgent investigation. Possible pathways include use of contaminated irrigation water, atmospheric deposition from lead-emitting sources such as battery recycling facilities, lead smelting operations, or combustion of leaded fuel if still in use, contamination from lead-containing dust or residues in the agricultural environment, use of lead-contaminated fertilizers or soil amendments, and natural geological sources if the bedrock contains significant lead mineralization. The observation that lead levels are uniformly high across all three varieties and all sampling sites suggests a

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widespread environmental contamination issue affecting the entire study area rather than isolated contamination events.

Comparison of heavy metals levels across Maize Varieties

When comparing heavy metal accumulation patterns across the three maize varieties, several important observations emerge. SC Duma 43 hybrid showed the highest levels for lead, zinc, and copper, suggesting this variety may be somewhat more efficient at metal uptake and translocation to grains. SC Sungura 301 exhibited the highest levels of cadmium and manganese. The indigenous Kamba variety generally fell in the middle range for most metals except manganese, where it showed much lower accumulation than the two hybrid varieties.

These varietal differences, while statistically significant in some cases, should not be overemphasized given that all three varieties showed unacceptable levels of lead and cadmium. The differences in uptake efficiency between varieties likely reflect genetic variations in root architecture, metal transporter expression, translocation mechanisms, and grain loading processes. Understanding these genetic factors could inform future breeding efforts aimed at developing maize varieties with reduced accumulation of toxic metals while maintaining or enhancing accumulation of essential micronutrients.

It is noteworthy that the modern hybrid varieties did not consistently show lower heavy metal accumulation compared to the traditional indigenous variety. This suggests that breeding programs that developed these hybrids focused primarily on yield and agronomic performance rather than mineral quality or food safety considerations. Future breeding efforts should incorporate screening for reduced toxic metal accumulation and enhanced essential mineral content to improve both safety and nutritional quality.

Implications of heavy metal levels for Food Safety and Public Health

The findings of this study reveal a serious food safety crisis in Masii Ward and potentially across broader areas of Machakos County. The maize varieties analysed, which represent common types cultivated and consumed in the region, contain lead and cadmium at levels far exceeding international safety standards. Consumption of this contaminated maize poses immediate and long-term health risks to the population, particularly vulnerable groups including children, pregnant women, and individuals with pre-existing health conditions.

The health implications are especially concerning given that maize serves as the primary staple food for most households in the study area. Unlike foods consumed occasionally or in small quantities, maize is eaten daily and forms the basis of multiple meals. This means that exposure to the heavy metal contamination is chronic, continuous, and at high doses. Over time, this chronic exposure will lead to progressive accumulation of cadmium and lead in body tissues, particularly kidneys, liver, and bones, eventually manifesting as clinical toxicity [7].

Children are especially vulnerable to heavy metal toxicity for several reasons. They absorb ingested metals more efficiently than adults, their developing nervous systems are more susceptible to neurotoxic effects, they have longer remaining lifespans for accumulated metals to cause damage, and they typically have higher food intake relative to body weight compared to adults. The neurodevelopmental effects of lead exposure in children can have lifelong consequences affecting educational achievement, economic productivity, and quality of life [14].

The concurrent deficiency in essential micronutrients like zinc, copper, and manganese compounds the public health problem. Populations consuming this maize face a double burden of toxic metal exposure combined with micronutrient malnutrition. Zinc and copper deficiencies impair immune function, potentially increasing susceptibility to infectious diseases. Iron deficiency, if also present due to low iron content in the maize or lead-induced anaemia, would further compromise health outcomes [15].

Potential Sources of Contamination

Identifying the sources of heavy metal contamination is essential for developing effective remediation strategies

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16]. The uniformly high levels of lead and cadmium across all three varieties and all sampling locations suggest widespread environmental contamination rather than variety-specific or site-specific issues.

Potential agricultural sources include long-term use of phosphate fertilizers that may contain cadmium as a natural contaminant derived from phosphate rock deposits, application of contaminated organic amendments such as manure from animals exposed to contaminated feed, use of pesticides containing metallic compounds, and irrigation with water contaminated by upstream industrial discharges or urban runoff [17]. The study area's proximity to urban centres and potential industrial activities could contribute atmospheric deposition of lead and other metals.

Soil contamination could also arise from historical use of leaded gasoline, if the area is near major roads where decades of vehicle emissions deposited lead, improper disposal or burning of lead-containing materials such as batteries, electronic waste, or painted materials, mining or quarrying activities that disturb lead-bearing geological formations, and natural geological sources if bedrock or parent soil materials contain elevated lead concentrations [18].

Distinguishing among these potential sources requires additional investigation including analysis of agricultural inputs used by farmers to test for metal contamination, testing of irrigation water sources for heavy metal content, analysis of soil samples from the farms to determine total metal content and bioavailable fractions, investigation of potential industrial or mining activities in the region that could release metals, and consultation with farmers about historical land use practices and inputs applied over time.

Studies Conducted in Kenya and other Countries

Studies in Kenya, Nigeria and Ghana reveal levels of heavy metal in maize grain is a worry to the consumer [19, 20, 21]. Levels of heavy metals in maize grains from different ecological zones in Uasin Gishu County, Kenya had mean concentration of Zn 0.122, Cd 0.03, Cu 0.111, Co 0.04 and Pb 0.33 mg/kg. These results were below WHO standards except for cadmium, cobalt and lead which were slightly higher than recommended standard. The study also found that maize leaves had mean concentration of Zn 0.115, Cd 0.04, Cu 0.117, Co 0.041 and Pb 0.323 mg/kg. These results were below WHO standards. The analytical results from this study provided important baseline statistics on the concentration of selected heavy metals in maize grains and leaves besides being an important assessment of environmental pollution in rural areas where maize farming is predominant [19].

A study was carried out to investigate the effect of industrial pollution that affected the metal concentration flared into the atmosphere, washed down by rain and absorbed by maize cultivated in industrial areas of Ogun State in Nigeria. The metal levels were suspected to have effects on food safety. The metal levels of Fe, Cu, Mg, Ni, Pb, and Co in maize ranged for Fe 28.5-59.5 mg/kg, Cu 2-10.7 mg/kg, Mg 248.3-321 mg/kg, Ni 1.8-4.775 mg/kg, Pb 62.5-150 mg/kg, and Co 1.2-10.2 mg/kg. Some of the metals including Ni in Ewekoro, Pb in Sango regions, exceeded the recommended limits set by WHO/FAO. The results showed that the high concentration of certain heavy metals in maize revealed the levels of food insecurity and this called for public concern [20].

Another study conducted from 10 communities in the Tolon District, northern region of Ghana, quantified the levels and measured the health risks of selected heavy metals in children and adults for Fe, Zn, Pb, Mn, Cr, Ni in milled maize and millet samples. In milled maize samples Fe levels were 1.3392 ± 0.4341 mg/kg, Ni 0.9502 ± 0.2696 mg/kg, Pb 2.2177 ± 0.0534mg/kg, Cr 0.4359 ± 0.3574 mg/kg, Zn 0.6809 ± 0.0534 mg/kg, and Mn 0.3550 ± 0.1042 mg/kg. Milled millet samples recorded mean concentration of metals as Fe 1.9467 ± 1.0597 mg/kg, Ni 0.9520 ± 0.1218 mg/kg, Pb 2.2780 ± 0.0221 mg/kg, Cr 0.3421 ± 0.1498 mg/kg, Zn 0.8540 ± 0.1139 mg/kg, and Mn 0.4241± 0.0859 mg/kg. All selected heavy metals concentrations were below standard in food except Pb. Locally made mill plates were found to leach heavy metals in the milled flours due to the direct contact of grains with the mill plates. However, the comparison of milled to pounded flour (control samples) indicated other potential sources of heavy metals contamination aside from the disk attrition mill. The health assessment revealed no potential hazards nor cancer risk in both children and adults [21].

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CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study successfully determined the levels of five heavy metals in three varieties of maize grown in Masii Ward, Machakos County, using Atomic Absorption Spectroscopy following optimized acid digestion. The findings reveal a critical food safety crisis that demands urgent attention from health authorities, agricultural extension services, and policymakers.

Among the five heavy metals analysed, lead exhibited the highest levels across all three maize varieties, ranging from 8.247 to 10.449 mg/g, levels that exceed regulatory limits by factors of 16 to 52. Cadmium was the second most abundant contaminant, with concentrations ranging from 0.562 to 1.998 mg/g, exceeding permissible limits by factors of 1 to 20. These findings indicate severe contamination with toxic metals that pose serious health risks to consumers.

In contrast, zinc, copper, and manganese were present at low levels, well below the recommended nutritional ranges of 30-95 mg/g for zinc, 10-50 mg/g for copper, and 5-20 mg/g for manganese. While these low levels do not pose toxicity risks, they indicate that the maize varieties provide inadequate amounts of essential micronutrients, potentially contributing to deficiency disorders in populations relying heavily on maize as their staple food.

SC Duma 43 hybrid generally showed the highest heavy metal levels, particularly for lead, followed by SC Sungura 301 and the indigenous Kamba variety. However, all three varieties exhibited unacceptable contamination levels that render them unsafe for human consumption according to international food safety standards established by WHO/FAO, and KEBS.

The health implications of consuming this contaminated maize are severe and multisystemic. Lead exposure at the levels detected would cause neurodevelopmental damage in children, cardiovascular disease and hypertension in adults, kidney damage, anaemia, and reproductive problems, with long-term carcinogenic risks. Cadmium contamination would lead to kidney disease, bone disease, liver damage, and increased cancer risk. The combination of toxic metal exposure with essential micronutrient deficiency creates a double burden of malnutrition affecting both immediate and long-term health outcomes.

The widespread nature of contamination across all varieties and sampling sites suggests that environmental contamination of soil, water, or both is the primary source rather than variety-specific characteristics. Urgent investigation is needed to identify specific contamination sources and pathways to enable targeted remediation efforts.

This research contributes valuable baseline data on heavy metal contamination in Kenyan maize that has been largely lacking in scientific literature. The findings demonstrate the critical need for regular monitoring of heavy metals in food crops, particularly staple foods consumed in large quantities. The study also highlights the importance of considering both food safety and nutritional quality when assessing crop suitability for human consumption.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Immediate action is needed to protect public health. Authorities should issue public health advisories warning residents of Masii Ward and potentially broader areas of Machakos County about the contamination risks associated with locally grown maize. Distribution and consumption of maize from contaminated areas should be restricted until safety can be assured. Alternative safe food sources should be made available to affected communities to prevent food insecurity while contamination issues are addressed.
2. Comprehensive soil testing should be conducted across farms in Masii Ward and surrounding areas to determine the extent and severity of heavy metal contamination in agricultural soils. This testing should include analysis of total metal content, bioavailable fractions, pH, organic matter, and other soil properties

affecting metal mobility. Based on soil testing results, appropriate soil remediation strategies should be implemented, which may include phytoremediation using metal-accumulating plants that are not consumed by humans or animals, soil amendments to reduce metal bioavailability such as lime to raise pH or organic matter to bind metals, removal and safe disposal of heavily contaminated topsoil in extreme cases, and crop rotation or land use changes to reduce human exposure pathways.

3. Water sources used for irrigation should be tested for heavy metal content to determine whether contaminated water is contributing to the problem. If irrigation water is found to be contaminated, alternative water sources should be identified or water treatment systems implemented to remove metals before agricultural use.
4. Agricultural practices should be modified to reduce metal accumulation in crops. Farmers should be advised to use low-cadmium phosphate fertilizers and to minimize unnecessary fertilizer applications. Organic soil amendments should be tested for metal content before application. Agricultural extension services should provide training on safe farming practices and integrated soil fertility management that enhances beneficial nutrients while minimizing contaminant inputs.
5. Research should be conducted on the specific sources of lead and cadmium contamination in the study area. This investigation should include surveys of potential industrial or mining activities, analysis of atmospheric deposition patterns, assessment of historical land use that might have introduced contaminants, and evaluation of all agricultural inputs including fertilizers, pesticides, manure, and irrigation water for metal content.
6. Plant breeding programs should incorporate screening for reduced toxic metal accumulation and enhanced essential mineral content. Varieties showing low uptake of lead and cadmium but efficient accumulation of zinc, copper, and other beneficial minerals should be identified and promoted. Genetic studies could elucidate the mechanisms underlying varietal differences in metal accumulation, informing marker-assisted selection for improved food safety and nutritional quality.
7. A comprehensive monitoring program should be established to regularly assess heavy metal levels in maize and other food crops from various regions of Machakos County and Kenya more broadly. This monitoring would provide early warning of contamination problems, track the effectiveness of remediation efforts, and generate data to support evidence-based food safety policies.
8. Health screening programs should be implemented for populations in affected areas to assess the extent of heavy metal exposure and health impacts. Blood lead and cadmium testing, along with assessment of kidney function and other health indicators, would identify individuals requiring medical intervention and provide data on the public health burden of contamination.
9. Public awareness campaigns should educate farming communities and consumers about heavy metal contamination risks, safe food handling and preparation practices that might reduce exposure, symptoms of heavy metal poisoning that should prompt medical attention, and the importance of dietary diversity to reduce dependence on potentially contaminated staple crops.
10. Policy interventions are needed at national and county levels to address food safety in agricultural systems. These should include establishment and enforcement of maximum permissible limits for heavy metals in agricultural soils and irrigation water, regulations requiring testing of agricultural inputs for contaminant content, mandatory food safety testing for crops from areas with known or suspected contamination, and development of compensation or support programs for farmers affected by contamination through no fault of their own.
11. Further research should be conducted to investigate the bioavailability and health effects of the specific metal forms present in these maize samples, assess the effectiveness of different cooking methods in reducing metal content or bioavailability, examine heavy metal levels in other food crops grown in the region, and evaluate the potential for using contaminated maize for non-food purposes such as animal feed with appropriate safety protocols or industrial uses that do not enter the food chain.

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