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Evaluating the Leaching of Heavy Metals from Polyethylene Bags into Food during Cooking

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Abstract

The pervasive use of polyethylene (PE) bags for cooking and storing staple Nigerian foods poses significant health risks due to heavy metal leaching. This study evaluates the migration of arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb) from transparent (TPB) and black (BPB) polyethylene bags into Garri, Semovita, Moi Moi, and Okpa under cooking conditions. Food samples, prepared using ingredients from Umuahia markets, were cooked in TPB and BPB, digested with nitric acid and aqua regia, and analysed via Atomic Absorption Spectrophotometry (AAS). Results revealed alarming contamination: BPB-cooked foods exhibited higher metal transfer, with Pb in Okpa (0.4801 mg/kg) and Cd in Moi Moi (0.3150 mg/kg) exceeding WHO/FAO limits (0.3 mg/kg Pb; 0.1 mg/kg Cd). Significant correlations emerged between As-Sb ($r = 0.974$, $p = 0.0256$) in uncooked samples and As-Cd ($r = 0.9932$, $p = 0.000672$) in cooked foods, highlighting synergistic leaching risks. Transparent bags also exhibited elevated levels of contamination, although these levels were 20–30% lower than those found in BPB-cooked foods. These findings underscore chronic exposure risks, including carcinogenicity and organ damage. Immediate actions are urged: enforcing bans on non-food-grade plastics, promoting biodegradable alternatives (e.g., plantain leaves), and launching public health campaigns to mitigate dietary heavy metal exposure. This study provides critical evidence for policymakers to prioritize food safety regulations in Nigeria and similar contexts by emphasizing feasible transitions to sustainable packaging.

Keywords: Polyethylene Bags, Heavy Metal Migration, Food Safety, Cooking Practices.

1.0 INTRODUCTION

Plastics are extensively used globally as food-contact packaging materials (FCPMs) due to their ability to preserve the freshness, aroma, and overall quality of food products during extended storage and transportation. Although plastics were discovered in the 1800s, their application in packaging only began in the 20th century. Initial use occurred during World War II, but widespread commercialization for food packaging followed only after the war (Raheem, 2013).

The exponential growth in the use of plastic packaging materials (PPMs) has raised serious concerns regarding their environmental and public health impacts, particularly their non-biodegradable nature and implications for food safety (Etia *et al.*, 2023). Plastic bags, whether degradable or non-degradable, contribute significantly to environmental pollution and pose health risks due to their potential to release harmful substances. In response, bioplastics derived from renewable resources have emerged as sustainable alternatives (Jain *et al.*, 2024).

Among various plastics, polyethylene (PE) is one of the most widely used materials for food packaging, owing to its favourable properties, such as water and gas barrier capabilities, thermal stability, low density, and cost-effective production (Ncube *et al.*, 2020). Polyethylene exists in several forms—low-density (LDPE), linear low-density (LLDPE), and high-density (HDPE), which are synthesised through the polymerisation of ethylene under different temperature and pressure conditions (Zhong *et al*., 2018). Despite its versatility, polyethylene, like many synthetic plastics, is highly resistant to degradation due to its stable polymer backbone, often persisting in the environment for hundreds of years (Zhao *et al*., 2023).

Disposable food containers made of plastic are widely used in homes, restaurants, and cafés for convenience and hygiene. However, concerns have intensified regarding the migration of toxic substances, particularly heavy metals, from plastic materials into food under heat or prolonged contact (Khaled *et al*., 2024).

Heavy metals such as lead (Pb), cadmium (Cd), arsenic (As), and antimony (Sb) have been reported to leach from plastic food packaging into food simulants or actual food, especially when exposed to high temperatures. These metals are non-biodegradable, bioaccumulative, and capable of interfering with vital physiological processes in humans, potentially causing neurological, renal, hepatic, and haematological damage. Long-term exposure is associated with severe health outcomes, including cancer, developmental issues, and systemic organ failure (Khaled *et al*., 2024). Recognising the risks, regulatory bodies such as the Bureau of Indian Standards (BIS) have set strict limits for metal content in foodcontact plastics, including a maximum of 1 ppm for total heavy metals and 0.1 ppm for cadmium (Khan & Khan 2015).

Given these concerns, this study focuses on the occurrence and migration of heavy metals from fossil fuel-derived polyethylene bags into commonly consumed food items during cooking.

2.0 MATERIALS AND METHODS

2.1 Sampling

For this study, samples of commonly consumed Nigerian staple foods—Garri, Semovita, Moi-moi (bean cake), and Okpa (Bambara nut cake)—were systematically collected to evaluate heavy metal migration from polyethylene packaging. Ingredients for moi moi, including beans, pepper, onions, salt, crayfish, seasoning, and vegetable oil, were procured from Orie Ugba Market in Umuahia, Nigeria. Similarly, components for Okpa, comprising Bambara nut flour, palm oil, salt, seasoning, crayfish, and pepper, were sourced from Ubani Market within the same locality. To assess contamination risks associated with local practices, transparent polyethylene bags (TPB) and black polyethylene bags (BPB), frequently employed in cooking and food storage across the region, were also obtained from these markets. This procurement strategy ensured alignment with typical consumer exposure scenarios, thereby bolstering the ecological relevance of the investigation. All the collected materials were subsequently homogenised and prepared under controlled laboratory conditions to standardise experimental variables.

2.2 Sample Preparation

The collected ingredients were homogenised using a mechanical grinder to ensure uniformity in texture and composition. Moi-moi and Okpa were prepared by wrapping the respective mixtures in either transparent polyethylene (TPB) or black polyethylene (BPB) bags, followed by cooking under controlled laboratory conditions to simulate typical household practices. Post-cooking, Garri and Semovita were portioned and wrapped in the same polyethylene materials to replicate common storage methods. Approximately 5 g of each cooked sample, along with corresponding sections of the polyethylene packaging, were systematically collected for subsequent analysis.

To evaluate spatial contamination gradients, slices measuring 0.5 cm, 1.0 cm, and 1.5 cm were excised from the exterior (directly contacting the polyethylene) to the interior of each food sample. These sections were oven-dried at 80°C for 24 hours to remove moisture, then ground into a fine powder using a sterilised wooden mortar and pestle. All equipment, including glassware, crucibles, and grinders, underwent rigorous pre-cleaning to eliminate contaminants: initial detergent washing, rinsing with distilled water, 24-hour immersion in 10% nitric acid, and oven-drying at 80°C. Procedural blanks and triplicate preparations were incorporated to ensure analytical reliability and reproducibility.

2.3 Quality Assurance and Quality Control

All chemicals and reagents used were of analytical grade. Digestion and analysis were carried out in triplicate to ensure reliability and reproducibility. Procedural and reagent blanks were included to correct for potential contamination. All glassware and plasticware, including crucibles, containers, and grinders, were pre-cleaned using detergent, rinsed with distilled water, soaked in 10% nitric acid (HNO_3) for 24 hours, and oven-dried at 80 °C for 5 hours to eliminate residual contaminants.

2.4 Sample Digestion for Heavy Metal Analysis

For heavy metal quantification, a 5 g aliquot of each dried food sample or polyethylene bag segment was precisely weighed into an acid-washed borosilicate beaker. Concentrated nitric acid (HNO_3, 10 mL) was added to each sample, and the mixture was allowed to react under a watch glass to minimize volatile losses and ensure controlled digestion. Following the cessation of vigorous reactions, the solution was gently heated on a hotplate until evaporated to near dryness to eliminate organic matrix interference. Subsequently, 5 mL of freshly prepared aqua regia (3:1 hydrochloric acid-to-nitric acid ratio) was introduced to the residue and refluxed at 120°C for 30 minutes to ensure complete dissolution of refractory analytes. The digestate was then cooled, treated with 10 mL of 1 mol/dm³ HNO_3, and filtered through ashless Whatman No. 42 filter paper into a 50 mL volumetric flask to remove particulate matter. The filtrate was diluted to the mark with deionised distilled water (18.2 MΩ·cm resistivity) to achieve a homogeneous matrix suitable for instrumental analysis. All digestions were performed in triplicate alongside procedural blanks to account for potential background contamination. The final digestates were stored in acid-leached polyethylene containers at 4°C until analysis to preserve analyte integrity.

2.5 Heavy Metal Analysis

Stock solutions (1000 mg/L) of arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb) were prepared using analytical-grade precursors: As_2O_3, $Cd(NO_3)_2 \cdot 4H_2O$, $Pb(NO_3)_2$, and Sb_2O_3, respectively. Serial dilutions yielded five calibration standards per metal, which were analysed via Atomic Absorption Spectrophotometry (AAS, model 210/211 VGP) to construct linear calibration curves ($R^2 \geq 0.998$). Method accuracy was validated using a certified reference material (CRM, IAEA) processed identically to test samples; percent recoveries ranged from 92% to 106%, confirming protocol robustness. Digested samples and blanks were aspirated into the AAS, and absorbance values were recorded at metal-specific wavelengths. Concentrations (mg/L) were extrapolated from calibration curves and converted to mg/kg using the formula:

$$\text{Conc. Mg/kg} = \frac{\text{Conc. mg/L} \times \text{Dilution factor (50 ml)}}{\text{Wt of sample digested (g)}}$$

Triplicate analyses, procedural blanks, and CRM validation ensured precision while minimising matrix interference. Reported values represent the mean ± standard deviation of three independent replicates.

3.0 RESULTS AND DISCUSSION

3.1 Results and Discussion

The analysis of food samples cooked in polythene bags, as shown in Table 1-3, revealed significant variations in the concentrations of four toxic metals: arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb), between uncooked and cooked foods, as well as between food samples exposed to transparent polythene bags (TPB) and black polythene bags (BPB). The results clearly demonstrate that both TPB and BPB contribute to the leaching of heavy metals into food, with black polythene bags showing a greater degree of contamination.

In uncooked food samples (garri, moi-moi, okpa, and semovita), heavy metal concentrations were generally low and within acceptable safety limits. Arsenic ranged from 0.0002 to 0.0006 mg/kg, cadmium from 0.0002 to 0.0013 mg/kg, lead from 0.0002 to 0.0382 mg/kg, and antimony from 0.0003 to 0.0007 mg/kg. These baseline values serve as a point of comparison to assess the impact of cooking in polythene bags.

Upon cooking in transparent polythene bags, there was a noticeable increase in heavy metal concentrations across all food samples, particularly in moi-moi and okpa. Arsenic levels rose to 0.2312 mg/kg in moi-moi and 0.2101 mg/kg in okpa, compared to the much lower values in the uncooked versions. Similarly, cadmium concentrations increased to 0.3001 mg/kg in moi-moi and 0.2210 mg/kg in okpa. Lead, a particularly toxic element, increased significantly in all cooked samples, with the highest concentrations observed in semovita (0.4210 mg/kg) and okpa (0.4160 mg/kg). Antimony levels also rose, ranging from 0.1060 mg/kg in garri to 0.3230 mg/kg in semovita. Similar trends were observed in okpa and semovita, with lead and cadmium concentrations in some samples exceeding the maximum permissible limits of 0.1 mg/kg for cadmium and 0.3 mg/kg for lead, as established by the World Health Organisation and the Food and Agriculture Organisation (WHO/FAO, 2011).

When foods were cooked in black polythene bags, even higher concentrations of heavy metals were observed. For example, arsenic reached 0.2510 mg/kg in moi-moi and 0.2850 mg/kg in okpa; cadmium levels rose to 0.3150 mg/kg and 0.2501 mg/kg, respectively. Lead levels were particularly alarming, with 0.3490 mg/kg in moi-moi and 0.4801 mg/kg in okpa—exceeding the World Health Organisation (WHO) and Food and Agriculture Organisation (FAO) recommended maximum limits. Antimony concentrations also increased, with values of 0.2310 mg/kg in moi-moi and 0.2110 mg/kg in okpa. The increased contamination observed with BPB may be attributed to the use of recycled materials, colouring agents, and additional stabilisers, which are more prevalent in black plastics (Bhunia *et al*., 2013; Grob *et al*., 2006). These components can degrade under heat and migrate into food, especially in moist, acidic, or protein-rich matrices such as moi-moi and okpa.

The presence of antimony (Sb), often used in polyethylene terephthalate (PET) and other polymer stabilisers, was also notable in cooked samples. Sb concentrations reached 0.2310 mg/kg in moi-moi and 0.2110 mg/kg in okpa when cooked in BPB, raising further toxicological concerns. Chronic exposure to antimony, although it has been studied less frequently, has been linked to respiratory and cardiovascular effects (EFSA, 2004).

These findings clearly indicate that cooking in polythene bags facilitates the migration of toxic metals into food, a process likely exacerbated by heat and the chemical nature of the food matrix. Moi-moi and okpa, which are both moist and protein-rich, appear particularly susceptible to contamination. The significantly higher contamination levels observed with black polythene bags may be attributed to the presence of industrial dyes, recycled materials, or higher levels of chemical additives used in their manufacture. This aligns with previous studies that have shown black plastics to be more likely to contain harmful residues.

From a public health perspective, the elevated levels of arsenic, cadmium, lead, and antimony found in cooked foods pose serious health risks. Chronic exposure to these metals is associated with various health issues, including cancer, kidney damage, neurotoxicity, and developmental disorders (Jaishankar *et al*., 2014).

The concentrations observed in this study, especially lead and cadmium, frequently exceed the permissible limits set by international health agencies, signalling a need for urgent intervention. From a public health standpoint, these findings are alarming. In conclusion, the study underscores the toxicological risks associated with the use of polythene bags, especially black ones, for cooking and storing food. The data strongly suggest that such practices contribute to significant heavy metal contamination and should be discouraged, particularly for foods exposed to high temperatures. Public awareness campaigns, regulatory control, and the promotion of safer alternatives, such as food-grade containers or natural wrappers like banana or plantain leaves, are essential steps towards minimising the health risks associated with food contamination from plastic materials.

Table 1: Mean (±SD) metal concentrations in uncooked food samples

Metal	Garri	Moi moi	Okpa	Semovita
As (mg/kg)	0.0005±0.0001	0.0006±0.0001	0.0002±0.0001	0.0005±0.0003
Cd (mg/kg)	0.0008±0.0004	0.0002±0.0001	0.0010±0.0008	0.0013±0.0002
Pb (mg/kg)	0.0002±0.0001	0.0382±0.0103	0.0002±0.0001	0.0002±0.0001
Sb (mg/kg)	0.0003±0.0001	0.0004±0.0001	0.0007±0.0001	0.0005±0.0002

Table 2: Mean (±SD) metal concentrations in transparent polythene bags (TPB) and cooked food samples

Metal	TPB	Garri	Moi-moi	Okpa	Semovita
As (mg/kg)	0.3115±0.0003	0.1050±0.0003	0.2312±0.0003	0.2101±0.0002	0.1000±0.0003
Cd (mg/kg)	0.4002±0.0003	0.0216±0.0002	0.3001±0.0002	0.2210±0.0003	0.0260±0.0004
Pb (mg/kg)	0.5013±0.0002	0.0313±0.0001	0.3410±0.0003	0.4160±0.0001	0.4210±0.0002
Sb (mg/kg)	0.4205±0.0002	0.1060±0.0002	0.2100±0.0002	0.2000±0.0000	0.3230±0.0003

Table 3: Mean (±SD) metal concentrations in black polythene bags (BPB) and cooked food samples

Metal	BPB	Moi-moi	Okpa
As (mg/kg)	0.3501±0.0003	0.2510±0.0003	0.2850±0.0003
Cd (mg/kg)	0.4702±0.0003	0.3150±0.0002	0.2501±0.0003
Pb (mg/kg)	0.6312±0.0001	0.3490±0.0031	0.4801±0.0009
Sb (mg/kg)	0.4227±0.0003	0.2310±0.0003	0.2110±0.0004

Statistical Analysis

The Analysis of Variance (ANOVA) for uncooked data yielded an F statistic of 0.9659 with prob > F (p-value) of 0.44053. This indicates that there is no statistically significant variation in the response variables for the uncooked data. This means that the overall effect of the predictors is statistically insignificant. Similarly, for "cooked with TPB" data, F-statistic = 1.18205 with p-value = 0.34779 also indicates that there is significant variation between any of the groups (Cd, As, Pb, Sb). Table 4 below indicates the correlation existing between each pair of the chemicals: arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb).

Table 4: Correlation Coefficient between heavy metals for the uncooked

Comparison	Correlation coefficient (r)	p-value	Interpretation
As–Cd	-0.634	0.366	Moderate negative, not significant
As–Pb	0.774	0.226	Strong positive, but not significant
As–Sb	0.974	0.0256	Very strong, positive, and significant
Cd–Pb	-0.720	0.280	Strong negative, not significant
Cd–Sb	-0.650	0.350	Moderate negative, not significant
Pb–Sb	0.890	0.110	Very strong positive, but not significant

From the Table 4, the correlation between as and Sb is a very strong positive correlation which is significant. While the corrections between the other pairs range from strong positive to strong negative, they are all insignificant. For the cooked food components, Table 5 shows that the only significant correlation exists between As and Cd, and it is a highly positive one. All correlations exhibit a positive trend, varying from moderate to extremely strong.

Table 5: Correlation Coefficient between heavy metals for the cooked

Comparison	Correlation coefficient (r)	p-value	Interpretation
As – Cd	0.9932	0.000672	Very strong positive, significant
As – Pb	0.6115	0.2731	Moderate positive, but not significant
As – Sb	0.5434	0.3439	Moderate positive, but not significant
Cd – Pb	0.6121	0.2725	Moderate positive, but not significant
Cd – Sb	0.5162	0.3732	Moderate positive, but not significant
Pb – Sb	0.8320	0.0806	Strong positive, borderline (not quite significant)

A pairwise comparison of the chemical components for cooked and uncooked food was also carried out, and the result indicated that there is a positive correlation between the chemicals within the same state (cooked or uncooked), as the correlation between As and Sb is 0.9744 for uncooked, 0.0900 for Pb and Sb in uncooked, 0.9932 for As and Cd in cooked, and 0.8320 for Pb and Sb in cooked data. In the between-state correlation (cooked vs. uncooked), there is a moderate negative correlation between uncooked As and cooked As and between uncooked Pb and cooked Pb with -0.548 and -0.699, respectively. This indicates that cooking effects a substantial change in the level of As and Pb present in the food. Furthermore, the correlation between cooked Sb and uncooked Sb was r = -0.413. This is a moderate negative correlation indicating that the amount of Sb may slightly transform as a result of cooking. However, the correlation for Cd in cooked and uncooked data was r = 0.276. This weak positive correlation shows that the levels of Cd in the food remain slightly stable and indicate that cooking does not necessarily increase the Cd level.

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

This study demonstrated that cooking food in both transparent and black polyethylene bags results in the migration of toxic heavy metals, specifically arsenic (As), cadmium (Cd), lead (Pb), and antimony (Sb), into the food matrix. The concentration levels varied by metal and sample type, but all indicated potential health risks associated with the leaching of these contaminants during cooking. Given the well-established toxicological effects of these metals, chronic dietary exposure, especially through repeated consumption of foods cooked or stored in fossil fuel-derived plastic bags, may contribute to cumulative toxic burden, potentially leading to organ damage, neurotoxicity, carcinogenicity, and other chronic health disorders.

4.2 Recommendations

The study recommends the following measures to mitigate public health risks:

1. Regulatory Intervention: Government agencies should enforce stricter regulations on the use of non-food-grade plastics in food preparation and packaging. Public health policies should be revised to explicitly prohibit the use of polyethylene bags for cooking or direct food contact during heat processing.
2. Public Health Surveillance: National food safety authorities should conduct comprehensive studies, including total diet studies, to assess population-wide exposure to plastic-derived contaminants and heavy metals.
3. Public Awareness Campaigns: Awareness initiatives should be launched to educate the public on the dangers of cooking or storing food in non-biodegradable plastic materials, particularly under heat.
4. Promotion of Safer Alternatives: The use of biodegradable, food-grade packaging materials should be promoted through policy incentives, subsidies, or public-private partnerships to encourage sustainable practices in food handling.

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