

Assessment of Heavy Metal Concentrations and Associated Health Risks in Nigeria-Branded and Marketed Sanitary Products Using Deterministic, Multivariate and Probabilistic Approaches

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Received: 9/02/2026

Revised: 21/02/2026

Accepted: 16/03/2026

Dermal exposure to heavy metals has emerged as a public health concern, particularly for women of reproductive age who regularly use sanitary pads and related materials for menstrual hygiene. Previous studies have shown that heavy metals and other contaminants present in sanitary products may be absorbed through the vulvar skin and vaginal mucosa during prolonged use. These tissues possess high permeability and absorption capacity, which may facilitate the entry of contaminants into systemic circulation. This study determined the concentrations of selected toxic heavy metals, namely lead (Pb), cadmium (Cd), arsenic (As), and chromium (Cr), in Nigerian-branded sanitary products and evaluated their potential health risks using deterministic, multivariate and probabilistic approaches. Five brands of sanitary pads, together with one brand each of panty liners, cotton wool and tissue paper from different batches, were randomly purchased from retail outlets in Lagos, Abuja and Port Harcourt, Nigeria. Samples were digested using a mixture of HNO₃ and H₂O₂ (5:1, v/v), and the metal concentrations were determined using atomic absorption spectrophotometry. Pb was detected in all sanitary products at concentrations ranging from 10.97 to 19.66 mg kg⁻¹. Cd and As were detected in several samples, with concentrations ranging from 1.31 to 2.10 mg kg⁻¹ and 0.92 to 4.85 mg kg⁻¹, respectively. Cr was present in all products at concentrations between 0.44 and 1.63 mg kg⁻¹. The concentrations of Pb, Cd and As exceeded safety limits established by the World Health Organization and the European Union, whereas Cr remained within permissible limits. Hazard Quotient and Hazard Index estimates indicated potential non-carcinogenic health risks, particularly from Pb and Cd, which contributed to the elevated risk observed for Besense Pad, Diva Pad and Toilet Roll. Multivariate and probabilistic analyses further supported these findings.

Keywords: Sanitary products, toxic metals, atomic absorption spectrophotometry, daily exposure dosage, hazard index, hazard quotient, Monte Carlo Simulations

Introduction

Millions of women around the world use sanitary products, such as tissue paper, cotton wool, tampons, and pads, as vital personal hygiene items. Given the frequency and sensitivity of the dermal contact involved, and the growing awareness of consumer exposure to environmental pollutants, their health safety has become a subject of global scrutiny. A growing body of research indicates that some commercial sanitary products may include traces of harmful heavy metals, such as Pb, Cr, Cd, and As (Kim *et al.*, 2019). Agricultural practices, such as irrigation with contaminated water, application of fertilizers and pesticides, and chemical treatments used for preservation of cotton, are known pathways by which heavy metals can be introduced into raw cotton (Atafar *et al.*, 2010; Suci *et al.*, 2022; Shen *et al.*, 2024). Moreover, the use of chemical additives, tainted raw materials, or insufficient quality control during manufacturing processes may further contribute to metal residues in finished products (Akinola & Olatunji, 2022). Similar patterns have been reported in other consumer and personal care products, where contamination has been linked to industrial activities,

recycling materials, and inadequate regulatory oversight (Chung, 2016; Kwak *et al.*, 2019).

Heavy metals, such as Pb, Cd, As, and Cr, are of particular concern due to their toxicity, persistence and capacity for bioaccumulation, even at low concentrations. Pb exposure has been associated with haematological disorders, neurotoxicity, and adverse reproductive outcomes (Jarup, 2003). Cd is recognised by the World Health Organization as a carcinogen and nephrotoxin that disrupts calcium metabolism (WHO, 2010). Cr, particularly in its hexavalent form, can induce oxidative stress and cause allergic dermatitis, while chronic exposure to As, even at low doses, is linked to an increased risk of cancer (Cho *et al.*, 2009).

Despite extensive investigations into heavy metal contamination in cosmetics and personal care products, data on sanitary materials remain scarce in many developing countries, including Nigeria. In such settings, regulatory enforcement, manufacturing oversight and product labelling are often inconsistent (USEPA, 2010). This study measured the levels of heavy metals in sanitary products marketed and branded in Nigeria and evaluated the safety implications of these products based on international regulatory standards.

Materials and Methods

Sample collection and preparation

Five different brands of sanitary pads, as well as a brand each of tissue paper, cotton wool, and panty liners (Besense) were purchased from retail stores in Lagos, Abuja, and Port Harcourt. Only locally produced brands with Nigerian labels were used for this study. These pad brands are namely, Virony, Joyland, My Girl, Besense, and Diva. Samples were randomly collected and preserved in their original container, kept dry, and examined prior to expiration. The samples were shredded into pieces to achieve homogeneity and oven-dried between 60 °C and 80 °C to constant weight. 1 g of each sample was then digested with a 10 mL mixture of nitric acid (HNO₃, 30% analytical grade) and hydrogen peroxide (H₂O₂) (v/v, 5:1) on a hotplate according to the Environmental Protection Agency's guideline, EPA Method 3050B. The acid digestion process was carried out in a fume cupboard for 15 - 30 mins. The digestion temperature was gradually increased from 80°C to 120 °C until the solution became clear. The solution was cool and filtered into a 50 mL volumetric flask. The filtrate was diluted to the 50 mL mark with deionized water.

Analytical determination

Concentrations of four heavy metals were determined using atomic absorption spectrophotometry (AAS; PerkinElmer AAnalyst 400). Two analytical approaches were employed. Pb, Cr, and Cd were quantified using flame atomic absorption spectrophotometry (FAAS), whereas As was determined using hydride generation atomic absorption spectrophotometry (HG-AAS).

For Pb, Cr, and Cd, digested samples were aspirated directly into the flame system for FAAS determination. Appropriate hollow cathode lamps were used for each element, and analytical wavelengths were set at the beginning of each metal analysis according to instrument specifications.

Arsenic determination required an additional pre-reduction step prior to analysis. Following digestion, arsenic in the samples was reduced from As(V) to As(III) to enable efficient hydride formation. The reduced samples were then analysed using the hydride generation system coupled to AAS, where arsine gas was generated and transported into the quartz cell for detection.

For all four metals, calibration curves were prepared from certified multi-element standards (Sigma-Aldrich, USA) at five concentration levels. The instrument was calibrated with these standards prior to sample analysis. Quantification accuracy was verified by assessing the linearity of the calibration curves, with correlation coefficients (R²) greater than 0.995. The limits of detection (LOD) ranged from 0.0023 to 0.008 mg kg⁻¹, while the limits of quantification (LOQ) ranged from

0.006 to 0.025 mg kg⁻¹. All samples were analysed in triplicate, and the relative standard deviation (RSD) for replicate measurements was maintained below 5% to ensure analytical precision.

Quality control

All glassware was soaked overnight in 10% HNO₃, washed and rinsed thoroughly with deionized water. Reagent blanks and replicate analyses were incorporated into every batch samples. Calibration accuracy was evaluated after every ten samples, and drifts greater than ±5% were recalibrated once observed. The limit of detection (LOD) and the limit of quantification (LOQ) were determined as three times and ten times the standard deviation of the blank signal divided by the mean blank response, respectively.

Data analysis

Data analyses were conducted using mean (±SD) and a two-way Analysis of Variance (ANOVA, p < 0.05) to test for inter-data variability. Tukey HSD post hoc test was conducted to compare the magnitude s of metal concentrations in sanitary products. Assumption diagnosis tests were conducted using Shapiro-Wilk's and Levene's test for normality, independence and homogeneity of variance. The non-carcinogenic health risk assessment was estimated using Hazard Quotient (HQ), and Hazard Index (HI) quantification according to the guidelines of USEPA (2010). Principal Component Analysis (PCA) and Monte Carlo Simulations (MCS) were conducted to support the health risk assessment based on HQ and HI.

Toxicological assessment

Heavy metal exposure was evaluated by calculating daily exposure doses (DED, mg.kg⁻¹.bw.d⁻¹), Hazard Quotients (HQ), and Indices (HI), and Associated Non-carcinogenic risk (NCR). The DEDs of heavy metals in the sanitary materials were calculated in accordance with Ma et al. (2024), expressed in equation (1).

$$DED = \frac{M \times Q \times N \times DA \times ED \times EF}{BW \times AT} \quad (1)$$

M is the heavy metal concentration (mg.kg⁻¹), Q indicates the weight of the sanitary pad or materials used (kg), N corresponds to the number of sanitary pads used per day, DA stands for the dermal absorption rate of heavy metals from sanitary materials (%), ED represents duration women are exposed to heavy metals via sanitary materials, EF corresponds to days per year women are exposed to heavy metals in sanitary materials, BW is the average women body weight (kg), and AT indicates the likely number of years in a woman's life. For non-carcinogenic risk, this is calculated as ED x 365 years. In this study, N is 4 pads per day; DA is 15% (Gao & Kannan, 2020), which is equivalent to 0.15 (Ma et al., 2024); ED is 5 days; EF is

60 days per year; BW is 70 kg for an average woman (5 kg less than that used by Gao & Kannan, 2020); and AT is $ED \times 365 = 1825$ days.

Hazard quotient (HQ) and hazard index (HI)

Human exposure to potentially toxic metals occurs through ingestion, inhalation, and skin contact (dermal absorption). To carry out non-carcinogenic risk evaluation that may potentially be caused by these metals, the hazard quotients and hazard indices of toxic heavy metals in sanitary materials were computed using equations (2) and (3), respectively. The accurate data from regulatory bodies on the reference dose (RfD) for toxic heavy metals via dermal absorption is not available. However, this study will leverage the data and assumptions from individual studies on the dermal absorption of these toxic metals. For that reason, the dermal absorption RfD (in $mg.kg^{-1}.day^{-1}$) for Pb, As, Cd and Cr are given as 5.3×10^{-4} , 1.23×10^{-4} (Abdullahi et al., 2022), 2.5×10^{-5} (Ma et al. 2019), and 6.0×10^{-5} (Ratnalu et al., 2021).

$$HQ = \frac{DED}{RfD(Dermal)} \quad (2)$$

$$HI = \sum(HQ_{Pb} + HQ_{As} + HQ_{Cd} + HQ_{Cr}) \quad (3)$$

Results and Discussion

Heavy metals

The results presented in Table 1 indicate that all five sanitary pad brands, as well as the other sanitary products analysed, contained measurable concentrations of heavy metals. Except where concentrations were below the limit of detection (LOD), the levels measured in the sanitary pads generally exceeded the permissible limits established by the European Chemicals Agency (ECHA), which specify maximum concentrations of 0.01 mg kg^{-1} for Pb, Cd and As, and 1.0 mg kg^{-1} for Cr (ECHA, 2018).

Pb was the most prominent pollutant among the sanitary products examined, with concentrations ranging from

$19.66 \pm 0.34 \text{ mg.kg}^{-1}$ in Virony Pad to $15.36 \pm 0.52 \text{ mg.kg}^{-1}$ in Diva (Table 1.0). The Pb levels in the panty liner samples were below the limit of detection (LOD). Since Pb is a recognized hazardous element with cumulative effects on the neurological, haematological, and reproductive systems, the comparatively high levels of Pb found in the majority of sanitary pads are concerning. Pb levels were found in excess of the allowable limits in all sanitary pads, indicating a lack of quality control. Cd and As had average contamination thresholds that exceeded the safe limits, but Cr levels were generally within the safe limits.

Cd was below the LOD in Virony Pad and Joyland Pad, but measurable amounts appeared in My Girl, Besense, and Diva pads, ranging from 1.31 to 2.1 mg.kg^{-1} . Cd concentrations were significantly higher than the ECHA (2018) limit and may be a sign of the presence of Cd-containing plasticisers or dyes. Only My Girl (0.92 mg.kg^{-1}) and Besense (4.85 mg.kg^{-1}) contained detectable levels of As. Given that As concentration in Besense was relatively high, over 400 times higher than the allowable limit, there is a huge concern that an As amount can trigger high toxicity and raise a potential for skin absorption. Cr concentrations varied from 0.57 to 1.15 mg.kg^{-1} for sanitary pads, with Virony marginally greater than the WHO/EU threshold of 1 mg.kg^{-1} . Bleach or pigments used in pad production were speculated to be the likely source of Cr.

Overall, the data show that the tested sanitary pads were heavily contaminated with heavy metals. The heavy metal levels surpassed global safety thresholds for all four metals. This is a clear indication of inadequate quality control and poor regulatory oversight on menstrual hygiene products. Persistent exposure through extended skin contact may present long-term health hazards, particularly for bioaccumulating metals, such as Pb and As.

Table 1: Concentrations of Different Brands of Sanitary Pads and other Sanitary Products made in Nigeria ($mg.kg^{-1}$)

Sanitary Brand	Pb	Cd	As	Cr
Virony Pad	19.66 ± 0.34	0.002 ± 0.001	0.002 ± 0.001	1.15 ± 0.05
Joyland Pad	16.17 ± 0.82	0.002 ± 0.001	0.002 ± 0.000	0.98 ± 0.04
My Girl Pad	17.67 ± 0.43	2.10 ± 1.27	0.92 ± 0.86	0.79 ± 0.03
Besense Pad	17.67 ± 0.52	1.84 ± 0.65	4.85 ± 0.33	0.86 ± 0.07
Diva Pad	15.36 ± 0.53	1.31 ± 1.00	0.002 ± 0.001	0.57 ± 0.04
Panty Liner (Besense)	0.002 ± 0.001	0.002 ± 0.001	0.002 ± 0.000	0.44 ± 0.02
Cotton Wool	10.97 ± 0.17	0.002 ± 0.000	1.70 ± 0.51	0.71 ± 0.02
Toilet Roll	12.93 ± 0.28	1.39 ± 1.08	0.002 ± 0.000	1.63 ± 0.03
ECHA (2018)	0.01	0.01	0.01	1.00

A two-way Analysis of Variance (ANOVA) with replication (Table 2) was conducted to examine differences in the toxic metal concentrations, measured

in triplicate, across the five brands of sanitary pads (Virony, Joyland, My Girl, Besense, and Diva) and across four types of toxic metals (Pb, Cd, As, and Cr).

The two-way ANOVA analysis with replication results (Table 2) show that the sanitary pad brand had statistically significant effect on toxic metal concentrations, the metal-type, and the brand versus metal-type. Given that the brand effects of the sanitary pads were significant ($F(4,40) = 88.614, p < 0.05$), this

clearly suggests that variability in metal concentrations differs among the five sanitary brands. Similarly, the metal-type had a highly significant effect on measured concentrations ($F(3,40) = 10352.627, p < 0.05$). A very large F-value reflects substantial differences in mean concentrations among the toxic metals analysed.

Table 2: The Analysis of Variance (ANOVA) between the Brands of Sanitary Pads and Toxic Heavy Metals with replication (at $\alpha = 0.05$ significance level)

Source of Variation	SS	df	MS	F	P-value	F crit
Sanitary Pad Brands	34.008	4	8.502	88.614	<0.001	2.61
Toxic Metals	2979.801	3	993.267	10352.627	<0.001	2.84
Pad vs Toxic Metals	65.230	12	5.436	56.657	<0.001	2.00
Residual (Error)	3.838	40	0.0959			
Total	3082.877	59				

Also, the brand versus metal interaction was significant ($F(12,40)=56.65, p<0.005$)(Figure 1). This indicates that the metal concentrations across brands were consistent for all metals. In other words, differences between brands depended on the specific metal type, while differences between metals varied by brand. Post hoc comparison using Tukey HSD indicated that Pb concentrations were relatively similar across the brands,

and were significantly higher than Cd, As, and Cr ($p<0.001$). Cd and As exhibited higher levels compared to others, the reason they are responsible for much of the brand-specific variability. Also, levels of Cd and As in My Girl and Bisense were higher when compared to other brands. Cr contributed comparatively little to the total variance.

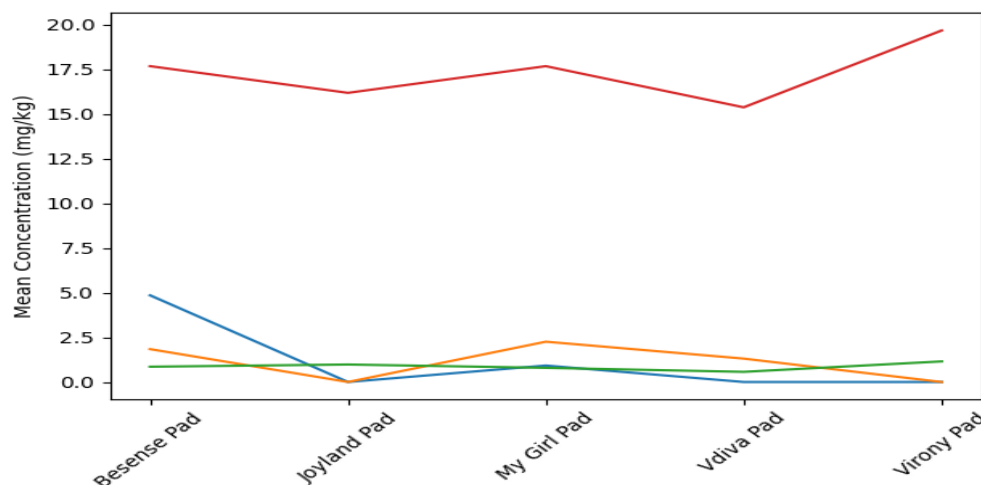


Figure 1: Plot of Metals and Sanitary Pad Interaction

Effect sizes were calculated and reported as partial eta squared (η^2) (Table 3). The magnitude of the effects was reflected in the very large partial eta squared values reported in Table 3 for sanitary pad type ($\eta^2 = 0.898$), metal type ($\eta^2 = 0.999$), and the pad-metal interaction

($\eta^2 = 0.944$). These results indicate that metal identity is the primary determinant of concentration variability. However, the strong pad-metal interaction suggests that the pattern of metal distribution differs significantly among brands.

Table 3: Evaluation of Effect Size Based on Sanitary Brand, Metal type, Metal-Pad interactions

Parameters	Partial Effect Size (η^2)
Sanitary Pad	0.898
Metal	0.999
Pad vs Metal	0.944

The assumptions of the two-way ANOVA, including independence, normality, and homogeneity of variances, were assessed using the Shapiro–Wilk and Levene’s tests. These assumptions did not affect the outcome of this analysis. Although residual diagnostics (Figures 2

and 3) indicated a mild deviation from normality in the upper tail, this deviation was not sufficient to affect the balanced design or the large effect sizes observed. Rather, they support the robustness of the statistical inference.

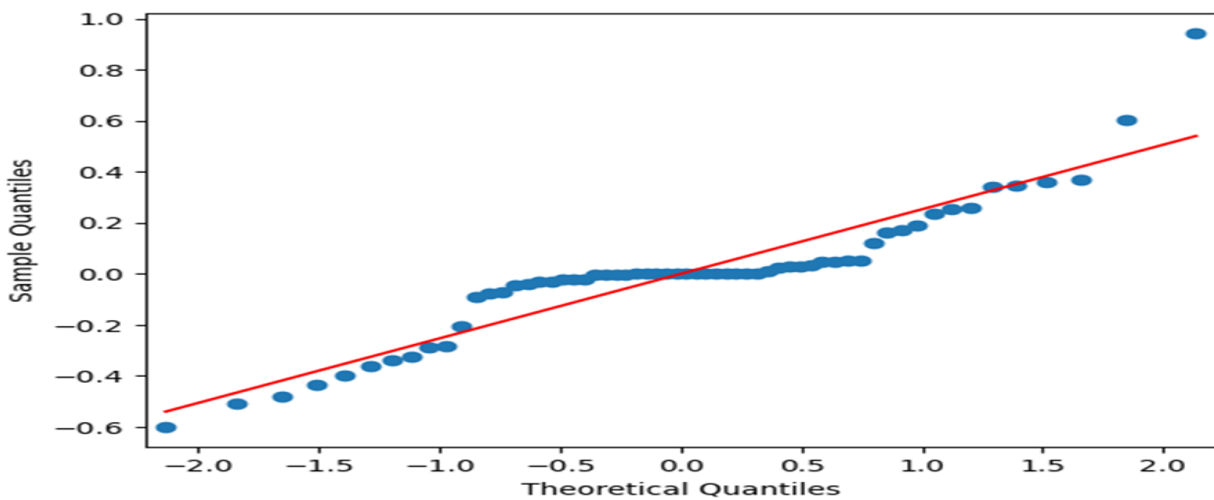


Figure 2: QQ Plots of Residuals for Normality and Independence Assessment

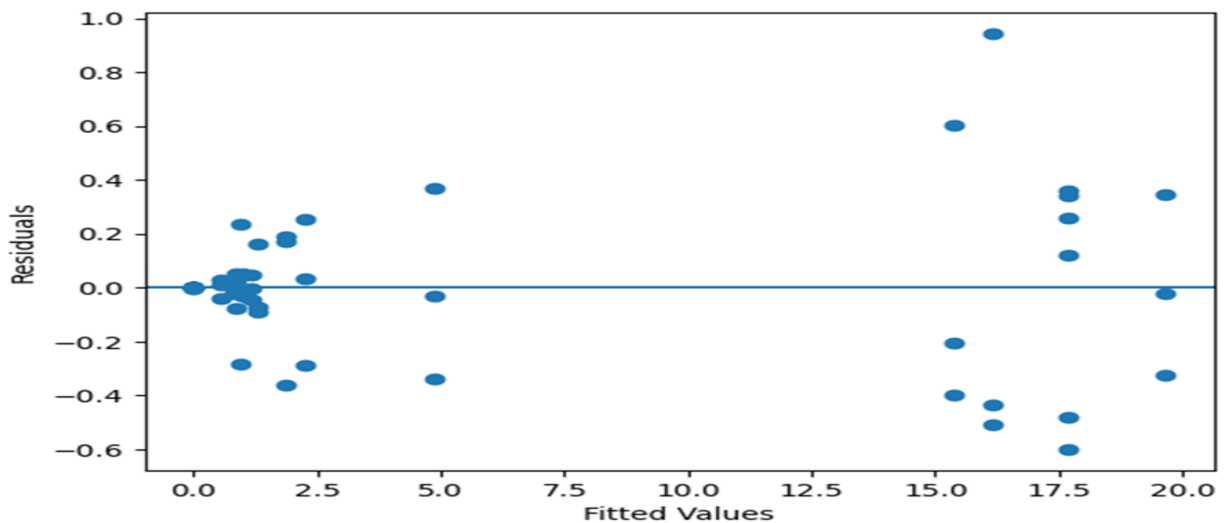


Figure 3: Plot of Residuals versus Fitted for Homogeneity Test

Principal component analysis (PCA)

The principal component analysis (PCA) was meant to standardise the metal concentration data for the purpose of exploring relationships between the toxic metals and the sanitary products. Four principal components were

extracted, and the first two were found to account for approximately 75.2% of the total variance (PC1:45.2%; PC2: 30.0%). Therefore, only the two were retained for data interpretation.

PC1 was characterised by strong negative loadings for Pb (-0.59) and Cd (-0.59), with a moderate contribution from As (-0.43). PC1 indicates a generalised heavy metal burden, which is widely dominated by Pb and Cr contributions across products. PC2 represented a strong positive loading for Cr (0.7), and a strong negative loading for As (-0.61). This indicates a strong differentiation between chromium-rich products and those influenced by As contamination.

The PCA score plot revealed marked separation among product categories. My Girl and Besense oriented away from other sanitary pads along the PC1 direction,

reflecting elevated Cd and As concentrations (Figure 4). The toilet roll was strongly separated and oriented along PC2 with comparatively high Cr content. Cotton wool took a distinct orientation, primarily influenced by As, while panty liners clustered near the origin, consistent with low metal concentrations.

The PCA loading plot further confirmed the correlation between Pb and Cd, which suggests common contamination characteristics. The opposing orientation of Cr and As along PC2 implies different sources or material-specific pathways for these elements.

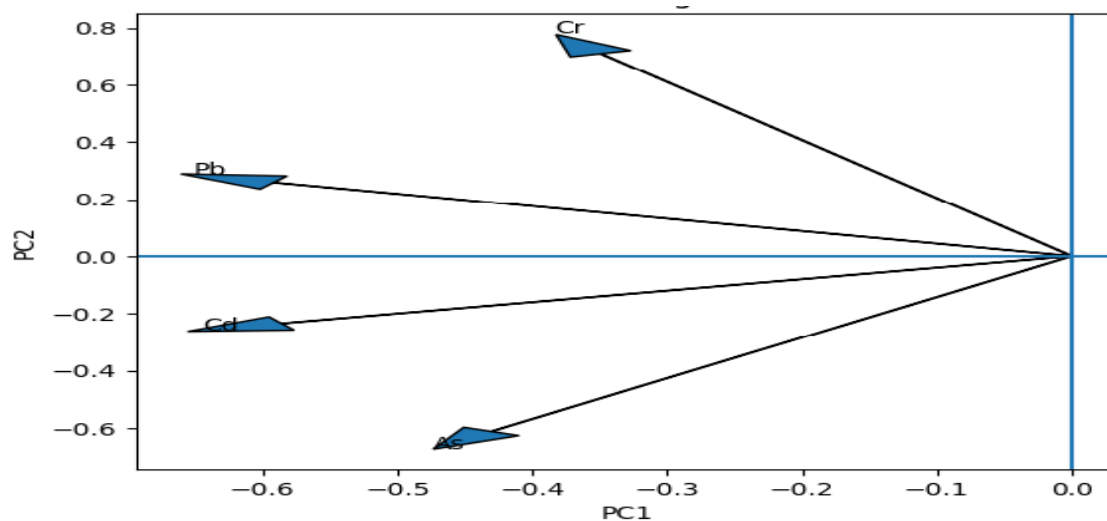


Figure 4: A PCA Loading Plot of Toxic Metals in Sanitary Products

Health risk assessment

Daily exposure dosage (DED)

This study estimated women's exposure to daily heavy metals from regular monthly sanitary use. The results indicated that lead (Pb) is the most uniform source of potential daily exposure, as it was found in almost all sanitary products. The greatest estimated exposure proportions occurred in all sanitary pads. As contributed to the daily exposure dosage in fewer sanitary products, such as My Girl, and Besense of the sanitary pads and Cotton wool (Table 4).

Trace levels of As contributed infrequently to daily exposure doses as they are only detected in My Girl, Besense, and cotton wool. Besense exhibited notably higher estimated daily exposure levels of As compared with other products. Cr was found to be the most common metal among the four across all product categories. It contributed to the daily exposure dosage of the sanitary products in the same way. The greatest

estimated daily Cr contribution was observed in toilet roll samples.

The highest cumulative daily exposure doses of the four toxic metals were associated with two brands of sanitary pads, My Girl and Besense. In contrast, Diva showed relatively lower daily exposure to Pb and no consistent exposure to As. Only Virony and Joyland sanitary pads were primarily linked to daily exposure to Pb and Cr.

Therefore, the results (Table 4) indicated that women who use sanitary products may be exposed to harmful amounts of metals on a daily basis during monthly cycles. Products that contain multiple detectable metals, especially My Girl and Besense, may contribute to comparatively higher estimated daily exposure doses. Pb is consistently detected, and Cr is present everywhere, indicating that these metals are the most common sources of potential exposure through sanitary materials.

Table 4: The daily exposure dosage (DED) of Toxic Heavy Metals in Sanitary Materials (measured in mg.kg⁻¹.bw.day⁻¹)

Sanitary Brand	Pb (x 10 ⁻⁴)	Cd (x 10 ⁻⁵)	As (x 10 ⁻⁵)	Cr (x 10 ⁻⁵)
Virony Pad	2.77	0.00	0.00	1.55
Joyland Pad	2.28	0.00	0.00	1.40
My Girl Pad	2.48	2.96	1.30	1.11
Besense Pad	2.49	2.59	6.83	1.21
Diva Pad	2.16	1.85	0.00	0.80
Panty Liner (Besense)	0.00	0.00	0.00	0.62
Cotton Wool	1.55	0.00	2.40	1.00
Toilet Roll	1.82	1.96	0.00	2.30

Hazard quotients and hazard indices

The Hazard Quotients (HQs) and Hazard Indices (HIs) for the four toxic metals in the analysed sanitary materials were calculated (Table 5). The panty liner exhibited the lowest Hazard Index. The HI values for the panty liner, Virony, Joyland, My Girl and cotton wool were all below unity, indicating negligible non-carcinogenic risk. In contrast, Besense, Diva and Toilet roll recorded HI values exceeding unity, suggesting the potential for adverse health effects upon prolonged human exposure.

The Hazard Index represents the combined non-carcinogenic risk associated with exposure to multiple metals. The HI values less than unity indicate negligible health risk, whereas values exceeding unity suggest the possibility of adverse health effects (USEPA, 2010). Among the products examined, Besense Pad exhibited the highest Hazard Index (HI = 2.27), exceeding the recommended safety threshold. This indicates a potential non-carcinogenic health concern associated with exposure to the combined heavy metals present in this product. Similarly, Toilet Roll (HI = 1.50) and Diva Pad (HI = 1.28) recorded Hazard Index values above unity, suggesting possible health risks upon prolonged exposure. In contrast, Virony Pad (HI = 0.78), Joyland Pad (HI = 0.66), My Girl Pad (HI = 0.95), Cotton Wool (HI = 0.65) and Panty Liner (HI = 0.10) exhibited Hazard Indices below the critical limit of 1. This clearly indicates a relatively low non-carcinogenic risk.

Pb contributed consistently to the Hazard Quotient across most products, producing values ranging from 0.29 to 0.52. This suggests that it is a major contributor to overall metal exposure. Cd showed significant contributions in Besense Pad (1.04), Toilet Roll (0.78) and Diva Pad (0.74), and this largely accounts for the elevated Hazard Index values observed for these products. Ar contributed moderately in Besense Pad (0.56) and Cotton Wool (0.19), while its contribution was negligible in the remaining samples. Cr generally contributed lower hazard quotients, although comparatively higher values were observed in Toilet Roll (0.38) and Virony Pad (0.26).

The persistent contributions of Pb and As to risk characterisation align with several recent investigations of sanitary products conducted globally. Surveys by Ma et al (2024) across seven countries reported moderate concentrations of Pb, Cd, and Cr and lower As levels in sanitary materials. Their study identified eight heavy metals, while the current research focused on four. Similarly, analysis of 30 samples of multi-brand tampons detected 16 measurable levels of heavy metals, including Pb, As, Cd, and Cr, in all products (Shearston et al., 2024). These findings further reinforce the assertion that metal contamination in hygienic products is universal.

The calculated non-carcinogenic risk (HI) of sanitary materials by Ma and co-workers (2024) was significantly lower than that obtained in this study. The contrast between the data may be due to differences in raw material sources, manufacturing quality, regulation standards, and the exposure assessment assumptions. The present study reported higher values than those reported in published studies. There is a possibility that the tested sanitary materials emanated from low-quality production chains or from highly contaminated raw materials.

The non-carcinogenic health risk estimates in this study were based on several limitations. Firstly, the exposure assumptions for heavy metals were adopted from other studies. These parameters formed the baseline for HQ evaluation, which includes the level of contact the material has with the skin, its frequency of use, and the level of metals absorbed. Secondly, the risk estimation approach also treats all forms of metals equally toxic, even though their real-world toxicity varies with oxidation states. These assumptions may skew the estimates. Furthermore, some sanitary products come directly in contact with mucosal tissue rather than the normal skin. The model does not fully account for the higher absorption that may occur in those areas. Finally, the present assessment considered only dermal exposure from sanitary materials, excluding other exposure sources. If other human exposure channels to heavy metals were explored, the total exposure level may exceed the current HQ and HI values.

Table 5: The Hazard Quotient (HQ) and Hazard Index (HI) of Toxic Heavy Metals in Sanitary Materials

Sanitary Brand	Pb	Cd	As	Cr	HI
Virony Pad	0.52	0.00	0.00	0.26	0.78
Joyland Pad	0.43	0.00	0.00	0.23	0.66
My Girl Pad	0.47	0.18	0.11	0.19	0.95
Besense Pad	0.47	1.04	0.56	0.20	2.27
Diva Pad	0.41	0.74	0.00	0.13	1.28
Panty Liner (Besense)	0.00	0.00	0.00	0.10	0.10
Cotton Wool	0.29	0.00	0.19	0.17	0.65
Toilet Roll	0.34	0.78	0.00	0.38	1.50

Monte Carlo simulation (MCS)

Monte Carlo simulation (MCS) is a computer-based probabilistic modelling technique commonly used to evaluate uncertainty in toxicity and health risk assessments in environmental studies. In this approach, probability distributions are assigned to key exposure variables, including metal concentrations in sanitary products, exposure frequency, dermal absorption rate, body weight of individuals, and duration of exposure. Sample values are randomly drawn from these distributions repeatedly and computed over thousands of iterations. This process generates a distribution of risk outcomes rather than a single deterministic value, thereby enabling estimation of the mean risk, maximum risk, and the probability of metals exceeding acceptable safety limits.

In this study, Monte Carlo simulations were conducted for metal concentrations in sanitary products using approximately 10,000 iterations. Truncated normal distributions were applied to the measured values. The

simulation outcomes indicated narrow ranges of uncertainty for Pb and Cr, reflecting low analytical variability (Figures 5a and 5d). The Pb distribution was approximately normal and peaked at 17.6 mg kg⁻¹, indicating stable concentrations, although levels were elevated across products. Cd displayed right-skewed variability, reflecting differences between very low values and elevated concentrations in certain products (Figure 5b). Conversely, Cd and As exhibited broader distributions, particularly in products where standard deviations were comparable to mean concentrations (Figures 5b and 5c). Arsenic showed the widest uncertainty band due to the high concentrations measured in Bisense. In contrast, Cr concentrations showed narrow dispersion, indicating consistent levels among brands. These findings highlight the importance of probabilistic approaches when evaluating metal exposure arising from heterogeneous occurrences across sanitary products.

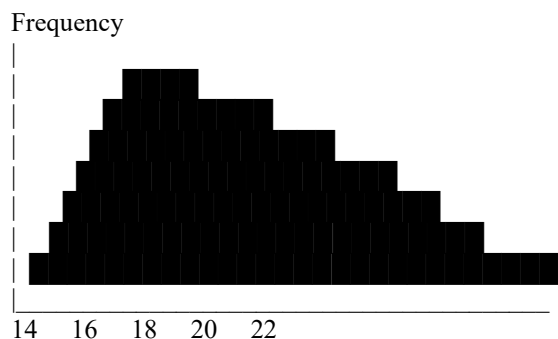


Figure 5(a): Monte Carlo Simulated Pb Concentration (mg/kg)

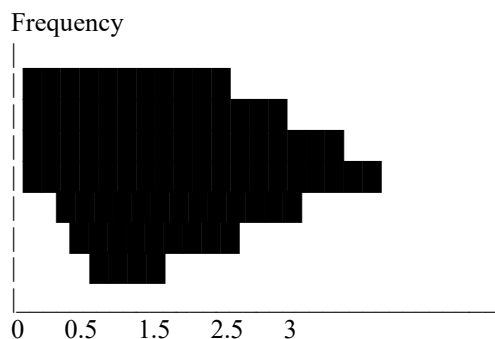


Figure 5(b): Monte Carlo Simulated Cd Concentration (mg/kg)

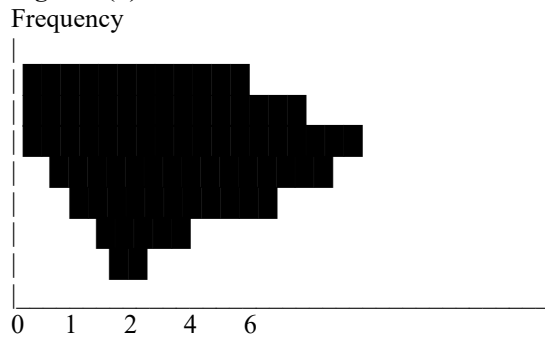


Figure 5(c): Monte Carlo Simulated As Concentration (mg/kg)

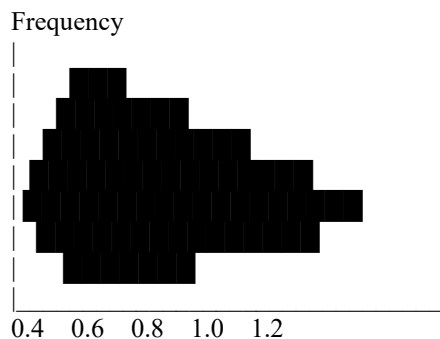


Figure 5(d): Monte Carlo Simulated Cr Concentration (mg/kg)

In summary, Pb, Cr and As are the key drivers of compositional variability and health risk assessment in sanitary products. These PCA and MCS data agree with the HQ and HI data generated earlier. From the results, Besense, Diva and Toilet roll may contribute to non-negligible dermal exposure to toxic metals. The panty liners consistently showed negligible risk ($HQ \ll 1$) for all toxic metals. The agreement between multivariate patterns and probabilistic risk estimation studies strengthens the product-specific contamination direction in this study, rather than the uniform background levels suspected.

Conclusion

This study examined heavy metal contamination and associated health risks in selected sanitary materials using deterministic, multivariate and probabilistic approaches. The results showed that the concentrations of Pb, Cd and As in several products exceeded the permissible limits set by the World Health Organization and the European Union, whereas Cr remained within acceptable regulatory thresholds. The health risk assessment revealed that the hazard quotient (HQ) for Ar in Besense and for Pb in all sanitary products exceeded unity, with the exception of panty liners, pointing to the potential non-carcinogenic health risks associated with regular use. Similarly, the hazard indices (HI) for three sanitary products surpassed the safety benchmark ($HI=1$), except for panty liners. This implies

possible cumulative health effects arising from combined metal exposure. The application of Principal Component Analysis and Monte Carlo Simulations strengthened the robustness of the health risk assessment. Both methods showed strong agreement with the HI outcomes, with Pb, Cr and As consistently regarded as key health risk contributors. Furthermore, multivariate and probabilistic analyses taken together demonstrated that heavy metal contamination and associated risks are product-specific, rather than uniform, across all sanitary materials. These findings advocate enhanced regulatory surveillance, routine product testing and stricter enforcement of safety standards to minimise potential health risks and ensure consumer protection, particularly in settings where regulatory oversight may be inconsistent. Finally, the Nigerian government's regulatory agency, such as NAFDAC, must make informed and proactive decisions to protect women's health, improve consumer's safety, and promote more sustainable production practices in support of Millennium Development Goals objectives on improving maternal health and ensuring a sustainable environment.

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