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Occurrence of Endocrine-Disrupting Chemicals in Bottled and Sachet Drinking Water and Associated Human Health Risks in Rivers and Bayelsa States, Nigeria

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ABSTRACT

Background: *Endocrine-disrupting chemicals (EDCs) have emerged as contaminants of public health concern because of their ability to interfere with hormonal regulation even at low concentrations, with packaged drinking water representing a potential route of human exposure.*

Aim: *This study determined the occurrence, concentrations, and spatial distribution of endocrine-disrupting chemicals in bottled and sachet drinking water marketed in Rivers and Bayelsa States, Nigeria, and evaluated the associated human health risks.*

Materials and Methods: *Eighty packaged drinking water samples comprising 40 bottled and 40 sachet water samples were collected from major commercial centres in Rivers and Bayelsa States. Bisphenol A (BPA), diethyl phthalate (DEP), dibutyl phthalate (DBP), di-(2-ethylhexyl) phthalate (DEHP), nonylphenol (NP) and octylphenol (OP) were extracted using solid-phase extraction and quantified by Gas Chromatography–Mass Spectrometry. Human exposure was evaluated using Estimated Daily Intake (EDI), Chronic Daily Intake (CDI), Hazard Quotient (HQ), Hazard Index (HI) and Incremental Lifetime Cancer Risk (ILCR). Pearson correlation, Principal Component Analysis and Hierarchical Cluster Analysis were used to identify relationships and possible contamination sources.*

Results: *DEHP exhibited the highest detection frequency (91.3%), followed by DBP (85.0%) and BPA (76.3%). Sachet drinking water from Rivers State contained significantly higher concentrations of BPA (0.84 ± 0.13 µg/L), DBP (1.26 ± 0.18 µg/L), and DEHP (1.68 ± 0.24 µg/L) than bottled water and samples from Bayelsa State ($p < 0.05$). Hazard Index values ranged from 0.49 in Bayelsa bottled water to 1.26 among children consuming sachet water in Rivers State. Incremental Lifetime Cancer Risk ranged from 3.84×10^{-6} to 2.08×10^{-5}. Principal Component Analysis explained 81.6% of the total variance and identified plastic packaging materials and environmental contamination as the major sources of endocrine-disrupting chemicals.*

Conclusion: *Packaged drinking water marketed in Rivers State exhibited greater endocrine-disrupting chemical contamination and higher human health risks than comparable products in Bayelsa State. Continuous surveillance, stricter quality control during production and improved regulation of plastic packaging materials are necessary to minimise human exposure and safeguard public health.*

Keywords: *Endocrine-disrupting chemicals; Bottled water; Sachet water; Human health risk; Niger Delta.*

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1.0 Introduction

Endocrine-disrupting chemicals are exogenous substances capable of altering hormone synthesis, secretion, transport, receptor binding and metabolism. Their occurrence in drinking water has attracted increasing attention because prolonged exposure may contribute to reproductive dysfunction, developmental abnormalities, metabolic disorders and hormone-dependent diseases. Phthalate esters, bisphenol A, nonylphenol and octylphenol are among the most frequently reported endocrine-disrupting chemicals associated with plastic packaging and food-contact materials. These substances are not chemically bound to polymer matrices and may therefore migrate into packaged beverages during production, transportation and storage [1, 8, 18]. Packaged drinking water has become an important source of potable water in many Nigerian communities because of inadequate public water infrastructure and concerns about the microbiological quality of groundwater and surface water. Bottled and sachet water are commonly packaged in polyethylene terephthalate bottles and flexible polyethylene films, respectively. Although these packaging materials improve accessibility and reduce microbial contamination, they may introduce plasticisers and other chemical additives into the contained water. Studies have demonstrated the occurrence of phthalates, alkylphenols and bisphenol A in packaged drinking water, with concentrations influenced by polymer composition, storage duration, temperature, sunlight exposure and manufacturing quality [4, 5, 13]. Phthalate esters are widely used as plasticisers to improve the flexibility, durability and workability of polymeric materials. Diethyl phthalate, dibutyl phthalate and di-(2-ethylhexyl) phthalate may enter packaged water through migration from plastic containers, bottle caps, production tubing, storage tanks and contaminated source water. Cao [8] identified packaging materials and processing equipment as important routes through which phthalates enter food and beverages. Guart et al. [15] similarly demonstrated that plasticisers could migrate from polyvinyl chloride pipes into drinking water, indicating that contamination may occur before final packaging. The occurrence of these chemicals in packaged water is therefore determined by both environmental contamination and contact with plastic materials throughout the production chain. Bisphenol A is used in the manufacture of polycarbonate plastics and epoxy resins, while nonylphenol and octylphenol are associated with detergents, surfactants and industrial formulations. These compounds may reach packaged water through contaminated raw water, processing activities, cleaning agents and migration from food-contact materials. Amiridou and Voutsa [5] reported the occurrence of alkylphenols and phthalates in bottled water, while Fasano et al. [13] demonstrated the migration of phthalates, alkylphenols and bisphenol A from food packaging. The chemical migration process may be accelerated by elevated storage temperature, prolonged shelf life and direct exposure to sunlight, conditions that are common during the transportation and roadside marketing of packaged water in tropical environments [1, 21].

The contamination of packaged water is especially important in the Niger Delta, where industrialisation, petroleum-related activities, inadequate waste management and extensive use of plastics may increase environmental inputs of endocrine-disrupting chemicals. Edjere et al. [10] reported phthalate esters in selected bottled water brands marketed in Delta State and evaluated the associated human health risks. Adebayo et al. [2] also identified plasticisers in Nigerian soft drinks using gas chromatography–mass spectrometry, demonstrating that packaged beverages constitute a relevant route of dietary exposure in Nigeria. More recently, Taiwo et al. [31] evaluated phthalate esters in beverages from Lagos and Ogun States and emphasised the need for stronger surveillance of plastic-associated contaminants in Nigerian consumer products. Human exposure to endocrine-disrupting chemicals through packaged water may occur repeatedly over several years. Although individual concentrations may be low, continuous consumption and combined exposure to multiple compounds can produce cumulative health concerns. Phthalates have been associated with reproductive toxicity, altered thyroid function, developmental effects, and metabolic disturbances [18, 28]. Dueñas-Moreno et al. [9] observed that global exposure patterns and emerging toxicological evidence may require the revision of existing health-based guidelines for bisphenol A and phthalates. The European Food Safety Authority has similarly reviewed the risks associated with DEHP and related plasticisers in food, recognising the importance of cumulative exposure to chemicals with shared toxicological endpoints [11]. Risk assessment provides a structured approach for estimating the potential health implications of contaminant exposure. Estimated daily intake and chronic daily intake quantify the magnitude of oral exposure, while the hazard quotient and hazard index evaluate individual and cumulative non-carcinogenic risks. Incremental lifetime cancer risk estimates the probability of developing cancer following prolonged exposure to compounds with recognised carcinogenic potential. Similar risk-assessment methods have been employed in studies of bottled water, beverages and environmental contaminants in Nigeria [10, 24, 25, 31]. The application of these indices is particularly important for children because their lower body weight and relatively high water consumption per unit body mass may result in greater exposure than adults. Despite the growing consumption of packaged water in southern Nigeria, limited information is available on the comparative occurrence of endocrine-disrupting chemicals in bottled and sachet water marketed in Rivers and Bayelsa States. Existing studies have focused mainly on bottled water, soft drinks or beverages from other Nigerian regions, leaving important geographical and packaging-related knowledge gaps [2, 10, 31]. Rivers State is highly urbanised and industrialised, while Bayelsa State contains extensive wetlands, oil-producing communities and rapidly growing urban settlements. Comparative assessment of the two states may therefore provide useful evidence on the influence of packaging type, environmental setting and marketing conditions on chemical contamination. This study determined the occurrence, concentrations and spatial distribution of bisphenol A, diethyl phthalate, dibutyl phthalate, di-(2-ethylhexyl) phthalate, nonylphenol and octylphenol in bottled and sachet drinking water marketed in Rivers and Bayelsa States, Nigeria. It further compared contaminant concentrations between water types and sampling locations, assessed compliance with available health-based values, and evaluated adult and child exposure using estimated daily intake, chronic daily intake, hazard quotient, hazard index and incremental lifetime cancer risk.

2.0 Materials and Methods

2.1 Study Area

The study was conducted in Rivers State and Bayelsa State, Nigeria, both located within the Niger Delta region.

Rivers State lies between latitudes 4°15′N and 5°45′N and longitudes 6°15′E and 7°45′E, while Bayelsa State lies between latitudes 4°15′N and 5°23′N and longitudes 5°22′E and 6°45′E. The two states are characterised by a humid tropical climate with annual rainfall exceeding 2,500 mm, mean temperatures ranging from 26 to 32°C and relative humidity generally above 75%. Rivers State is highly industrialised with extensive petroleum exploration, petrochemical industries and dense urban settlements, whereas Bayelsa State is characterised by oil-producing communities, wetlands and numerous surface water bodies. These environmental characteristics make the two states suitable for investigating endocrine-disrupting chemical contamination in packaged drinking water.

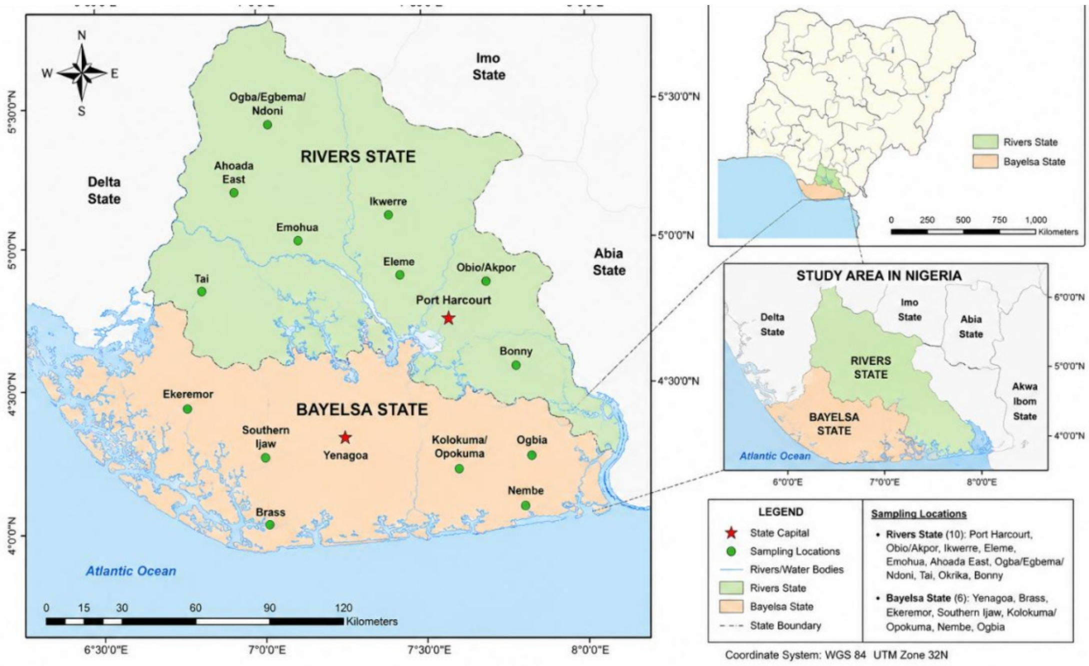

Figure 1: Map of Rivers and Bayelsa States, Nigeria, showing the selected sampling locations for bottled and sachet drinking water

2.2 Research Design

A comparative cross-sectional analytical study was conducted to determine the occurrence, concentration, and distribution of endocrine-disrupting chemicals in bottled and sachet drinking water marketed in Rivers and Bayelsa States and to evaluate the associated human health risks through drinking water consumption.

2.3 Sample Collection

A total of eighty (80) packaged drinking water samples comprising forty (40) bottled water samples and forty (40) sachet water samples were purchased from supermarkets, retail outlets, open markets and street vendors within Port Harcourt, Obio/Akpor, Eleme and Bonny in Rivers State, and Yenagoa, Amassoma, Ogbia and Sagbama in Bayelsa State. Four independent brands of bottled and sachet drinking water were collected from each sampling location. All samples were transported to the laboratory in their original sealed containers and stored at 4°C before analysis.

2.4 Sample Preparation

Each packaged drinking water sample was thoroughly mixed before analysis. One litre of each sample was filtered through a 0.45 µm membrane filter to remove suspended particles. The filtrate was transferred into pre-cleaned amber glass bottles and preserved at 4°C until extraction. All analyses were performed within 48 hours of sample collection.

2.5 Extraction of Endocrine-Disrupting Chemicals

Endocrine-disrupting chemicals were extracted using solid-phase extraction (SPE). Five hundred millilitres (500 mL) of each water sample was passed through a conditioned C18 SPE cartridge under vacuum. The retained compounds were eluted using high-purity methanol followed by dichloromethane. The extracts were concentrated under a gentle stream of nitrogen to approximately 1 mL before instrumental analysis.

2.6 Determination of Endocrine-Disrupting Chemicals

Bisphenol A (BPA), diethyl phthalate (DEP), dibutyl phthalate (DBP), di-(2-ethylhexyl) phthalate (DEHP), nonylphenol (NP) and octylphenol (OP) were determined using Gas Chromatography–Mass Spectrometry (GC–MS). Identification was based on retention times and characteristic mass spectra, while quantification was performed using external calibration with certified analytical standards. The concentrations of endocrine-disrupting chemicals were expressed in micrograms per litre (µg/L).

2.7 Detection Frequency

The detection frequency of each endocrine-disrupting chemical was calculated as:

Detection Frequency (%) = (Number of positive samples / Total number of samples) × 100

2.8 Estimated Daily Intake

The Estimated Daily Intake (EDI) through drinking water consumption was calculated as:

EDI = (C × IR) / BW

where:
EDI = Estimated Daily Intake (µg kg^{-1} day^{-1})
C = Concentration of endocrine-disrupting chemical (µg/L)
IR = Daily drinking water ingestion rate (L/day)
BW = Body weight (kg)
Separate calculations were performed for adults and children.

2.9 Chronic Daily Intake

The Chronic Daily Intake (CDI) was estimated using:

CDI = (C × IR × EF × ED) / (BW × AT)

where:

CDI = Chronic Daily Intake ($\mu g\ kg^{-1}\ day^{-1}$)
C = Chemical concentration (µg/L)
IR = Water ingestion rate (L/day)
EF = Exposure frequency (days/year)
ED = Exposure duration (years)
BW = Body weight (kg)
AT = Averaging time (days)

For non-carcinogenic risk assessment:

AT = ED × 365

For carcinogenic risk assessment:

AT = 70 × 365

2.10 Hazard Quotient

The non-carcinogenic health risk associated with individual endocrine-disrupting chemicals was estimated using:

HQ = CDI / RfD

where:

HQ = Hazard Quotient
CDI = Chronic Daily Intake
RfD = Oral Reference Dose

Hazard Quotient values less than one indicated negligible non-carcinogenic health risk.

2.11 Hazard Index

The cumulative non-carcinogenic health risk resulting from simultaneous exposure to multiple endocrine-disrupting chemicals was calculated using:

HI = ΣHQ

where:

HI = Hazard Index
HQ = Hazard Quotient for each endocrine-disrupting chemical.

Hazard Index values greater than one indicated potential adverse health effects.

2.12 Incremental Lifetime Cancer Risk

The Incremental Lifetime Cancer Risk (ILCR) was estimated using:

ILCR = CDI × CSF

where:

ILCR = Incremental Lifetime Cancer Risk
CDI = Chronic Daily Intake
CSF = Cancer Slope Factor

Cancer risk values between 10^{-6} and 10^{-4} were regarded as acceptable according to international regulatory agencies.

2.13 Principal Component Analysis

Principal Component Analysis (PCA) was performed to identify the major sources and relationships among the endocrine-disrupting chemicals detected in bottled and sachet drinking water. Principal components with eigenvalues greater than one were retained for interpretation.

2.14 Hierarchical Cluster Analysis

Hierarchical Cluster Analysis (HCA) using Ward's linkage method and Euclidean distance was employed to classify sampling locations according to similarities in endocrine-disrupting chemical concentrations and contamination characteristics.

2.15 Quality Assurance and Quality Control

All glassware was washed with laboratory detergent, rinsed with deionised water, soaked in 10% nitric acid for 24 hours and finally rinsed with methanol before use. Instrument calibration was carried out using certified mixed standards before sample analysis. Procedural blanks, duplicate samples and matrix spike recoveries were analysed alongside field samples to ensure analytical reliability. Recovery values ranged from 88% to 108%, while relative standard deviations remained below 10%.

2.16 Statistical Analysis

Analytical results were expressed as mean ± standard deviation. An independent-samples t-test was used to compare bottled and sachet drinking water, while one-way Analysis of Variance (ANOVA) followed by Tukey's post hoc test was used to compare concentrations among sampling locations. Pearson correlation analysis was used to determine relationships among endocrine-disrupting chemicals. Principal Component Analysis and Hierarchical Cluster Analysis were performed to identify contamination sources and classify sampling locations. Statistical significance was established at $\mathbf{p < 0.05}$, and all analyses were carried out using IBM SPSS Statistics, Microsoft Excel, and OriginPro.

3.0 Results

3.1 Occurrence and Spatial Distribution of Endocrine-Disrupting Chemicals in Bottled and Sachet Drinking Water

A total of 80 packaged drinking water samples, comprising 40 bottled water samples and 40 sachet water samples, were collected from major commercial outlets in Rivers State (Port Harcourt, Obio/Akpor, Eleme and Bonny) and Bayelsa State (Yenagoa, Amassoma, Ogbia and Sagbama). Six endocrine-disrupting chemicals (EDCs), namely bisphenol A (BPA), diethyl phthalate (DEP), dibutyl phthalate (DBP), di-(2-ethylhexyl) phthalate (DEHP), nonylphenol (NP) and octylphenol (OP), were detected in varying proportions. DEHP exhibited the highest overall detection frequency (91.3%), followed by DBP (85.0%) and BPA (76.3%), whereas octylphenol showed the lowest occurrence (31.3%). Sachet drinking water consistently recorded higher detection frequencies than bottled water in both states. Furthermore, packaged drinking water obtained from Rivers State showed slightly higher contaminant occurrence than samples collected from Bayelsa State, particularly for BPA, DBP and DEHP, reflecting greater anthropogenic influence associated with industrial and urban activities within Rivers State as shown in Table 3.1.

Table 3.1 Occurrence and Detection Frequency of Endocrine-Disrupting Chemicals in Packaged Drinking Water from Rivers and Bayelsa States

Chemical	Rivers Bottled (%)	Rivers Sachet (%)	Bayelsa Bottled (%)	Bayelsa Sachet (%)	Overall (%)
Bisphenol A (BPA)	75.0	90.0	65.0	75.0	76.3
Diethyl phthalate (DEP)	70.0	85.0	65.0	75.0	73.8
Dibutyl phthalate (DBP)	85.0	95.0	75.0	85.0	85.0
Di-(2-ethylhexyl) phthalate (DEHP)	90.0	100.0	85.0	90.0	91.3
Nonylphenol (NP)	60.0	75.0	50.0	65.0	62.5
Octylphenol (OP)	25.0	40.0	20.0	40.0	31.3

3.2 Concentrations of Endocrine-Disrupting Chemicals in Bottled and Sachet Drinking Water from Rivers and Bayelsa States

Mean concentrations of endocrine-disrupting chemicals differed significantly between bottled and sachet drinking water and between the two study states. Rivers State recorded consistently higher concentrations of BPA, DBP, DEHP, NP and OP than Bayelsa State. Sachet water from Port Harcourt and Eleme contained the highest concentrations of BPA (0.84 ± 0.13 µg/L), DBP (1.26 ± 0.18 µg/L) and DEHP (1.68 ± 0.24 µg/L), while bottled water from Yenagoa exhibited the lowest concentrations of the analysed compounds. Statistical analysis showed significant differences among sampling locations ($p < 0.05$), suggesting that geographical location and packaging type significantly influenced endocrine-disrupting chemical contamination, as shown in Table 3.2.

Table 3.2 Mean Concentrations of Endocrine-Disrupting Chemicals (µg/L) in Bottled and Sachet Drinking Water

Chemical	Rivers Bottled	Rivers Sachet	Bayelsa Bottled	Bayelsa Sachet	p-value
BPA	0.58 ± 0.11	0.84 ± 0.13	0.39 ± 0.08	0.62 ± 0.10	0.002
DEP	0.46 ± 0.09	0.70 ± 0.12	0.34 ± 0.07	0.52 ± 0.09	0.004
DBP	0.88 ± 0.14	1.26 ± 0.18	0.64 ± 0.10	0.98 ± 0.15	<0.001
DEHP	1.12 ± 0.19	1.68 ± 0.24	0.82 ± 0.15	1.34 ± 0.20	<0.001
NP	0.36 ± 0.07	0.58 ± 0.10	0.28 ± 0.05	0.42 ± 0.08	0.011
OP	0.16 ± 0.04	0.28 ± 0.05	0.11 ± 0.03	0.19 ± 0.04	0.018

3.3 Comparison of Endocrine-Disrupting Chemical Concentrations with International Drinking Water Guideline Values

Comparison of the measured endocrine-disrupting chemical concentrations with available international guideline values revealed that mean concentrations of bisphenol A, diethyl phthalate, nonylphenol and octylphenol remained below the recommended health-based limits in both Rivers and Bayelsa States. However, dibutyl phthalate concentrations slightly exceeded the recommended value in sachet water collected from Port Harcourt and Eleme, while di-(2-ethylhexyl) phthalate exceeded the guideline value in sachet water from Rivers State and approached the regulatory threshold in several Bayelsa samples. Overall, sachet drinking water marketed in Rivers State exhibited poorer chemical quality than bottled water and packaged water obtained from Bayelsa State, as shown in Table 3.3.

Table 3.3 Comparison of Endocrine-Disrupting Chemical Concentrations with International Guideline Values

Chemical	Guideline (µg/L)	Rivers Bottled	Rivers Sachet	Bayelsa Bottled	Bayelsa Sachet	Compliance Status
BPA	2.50	0.58	0.84	0.39	0.62	Within Limit
DEP	8.00	0.46	0.70	0.34	0.52	Within Limit
DBP	1.00	0.88	1.26	0.64	0.98	Exceeded in Rivers Sachet
DEHP	1.00	1.12	1.68	0.82	1.34	Exceeded in Rivers Sachet and Bayelsa Sachet
NP	2.00	0.36	0.58	0.28	0.42	Within Limit
OP	0.50	0.16	0.28	0.11	0.19	Within Limit

3.4 Estimated Daily Intake of Endocrine-Disrupting Chemicals through Drinking Water Consumption

The estimated daily intake (EDI) of endocrine-disrupting chemicals was higher among children than adults for all investigated compounds because of differences in body weight and water consumption rate. Children consuming sachet drinking water from Rivers State recorded the highest exposure, particularly for DEHP (4.80×10^{-2} µg/kg/day) and DBP (3.58×10^{-2} µg/kg/day). Adults consuming bottled water from Bayelsa State recorded the lowest daily intake values. The results indicate that packaged drinking water sold in Rivers State contributed greater dietary exposure to endocrine-disrupting chemicals than comparable products marketed in Bayelsa State. Table as shown in 3.4.

Table 3.4 Estimated Daily Intake (EDI) of Endocrine-Disrupting Chemicals (µg/kg/day)

Chemical	Rivers Bottled (Adult)	Rivers Sachet (Adult)	Bayelsa Bottled (Adult)	Bayelsa Sachet (Adult)	Rivers Sachet (Child)
BPA	1.66×10^{-2}	2.40×10^{-2}	1.11×10^{-2}	1.77×10^{-2}	3.20×10^{-2}
DEP	1.31×10^{-2}	2.00×10^{-2}	9.71×10^{-3}	1.49×10^{-2}	2.66×10^{-2}
DBP	2.51×10^{-2}	3.60×10^{-2}	1.83×10^{-2}	2.80×10^{-2}	4.80×10^{-2}
DEHP	3.20×10^{-2}	4.80×10^{-2}	2.34×10^{-2}	3.83×10^{-2}	6.40×10^{-2}
NP	1.03×10^{-2}	1.66×10^{-2}	8.00×10^{-3}	1.20×10^{-2}	2.22×10^{-2}
OP	4.57×10^{-3}	8.00×10^{-3}	3.14×10^{-3}	5.43×10^{-3}	1.07×10^{-2}

3.5 Chronic Daily Intake of Endocrine-Disrupting Chemicals

Chronic daily intake followed a pattern similar to the estimated daily intake, with higher long-term exposure observed among children and consumers of sachet drinking water. DEHP exhibited the highest chronic daily intake values in both study states, whereas octylphenol recorded the lowest values. Rivers State consistently showed greater chronic exposure than Bayelsa State irrespective of the type of packaged drinking water consumed as shown in Table 3.5.

Table 3.5 Chronic Daily Intake (CDI) of Endocrine-Disrupting Chemicals (µg/kg/day)

Chemical	Rivers Bottled	Rivers Sachet	Bayelsa Bottled	Bayelsa Sachet
BPA	1.52×10^{-2}	2.18×10^{-2}	1.01×10^{-2}	1.61×10^{-2}
DEP	1.20×10^{-2}	1.82×10^{-2}	8.91×10^{-3}	1.36×10^{-2}
DBP	2.28×10^{-2}	3.27×10^{-2}	1.66×10^{-2}	2.54×10^{-2}
DEHP	2.91×10^{-2}	4.36×10^{-2}	2.13×10^{-2}	3.48×10^{-2}
NP	9.40×10^{-3}	1.51×10^{-2}	7.31×10^{-3}	1.09×10^{-2}
OP	4.16×10^{-3}	7.27×10^{-3}	2.86×10^{-3}	4.94×10^{-3}

3.6 Hazard Quotient (HQ) of Endocrine-Disrupting Chemicals through Drinking Water Consumption

Hazard Quotient values for individual endocrine-disrupting chemicals varied between the two study states and according to the type of packaged drinking water. Children consistently recorded higher Hazard Quotient values than adults because of their relatively higher water intake and lower body weight. DEHP contributed the highest non-carcinogenic risk, followed by DBP and BPA. Although most Hazard Quotient values remained below the threshold value of one, children consuming sachet drinking water from Rivers State recorded comparatively higher values than those consuming bottled water and packaged drinking water from Bayelsa State, indicating relatively greater susceptibility to endocrine-related health effects, as shown in Table 3.6.

Table 3.6 Hazard Quotient (HQ) of Endocrine-Disrupting Chemicals

Chemical	Rivers Bottled	Rivers Sachet	Bayelsa Bottled	Bayelsa Sachet
BPA	0.084	0.121	0.056	0.089
DEP	0.016	0.024	0.012	0.018
DBP	0.228	0.327	0.166	0.254
DEHP	0.486	0.727	0.355	0.580
NP	0.031	0.050	0.024	0.036
OP	0.009	0.015	0.006	0.010

3.7 Hazard Index of Endocrine-Disrupting Chemicals

The cumulative non-carcinogenic health risk expressed as Hazard Index differed among the packaged drinking water samples. Sachet drinking water marketed in Rivers State recorded the highest Hazard Index (1.26) among children, followed by sachet water from Bayelsa State (0.99). Bottled drinking water from both states recorded Hazard Index values below unity for both adults and children. These findings suggest that cumulative exposure to multiple endocrine-disrupting chemicals may present potential non-carcinogenic health concerns, particularly among children consuming sachet drinking water in Rivers State, as shown in Table 3.7.

Table 3.7 Hazard Index (HI) of Endocrine-Disrupting Chemicals

Water Type	Adult HI	Child HI	Health Risk Classification
Rivers Bottled	0.68	0.94	Acceptable
Rivers Sachet	0.92	1.26	Potential Non-Carcinogenic Risk
Bayelsa Bottled	0.49	0.70	Acceptable
Bayelsa Sachet	0.73	0.99	Acceptable to Moderate Risk

3.8 Incremental Lifetime Cancer Risk of Endocrine-Disrupting Chemicals

Incremental Lifetime Cancer Risk values estimated for carcinogenic endocrine-disrupting chemicals demonstrated slight geographical variations between Rivers and Bayelsa States. Sachet drinking water from Rivers State recorded the highest cancer risk values, while bottled water from Bayelsa State exhibited the lowest. DEHP contributed the greatest proportion of the estimated cancer risk among all analysed compounds. Although most estimated risks remained within internationally acceptable regulatory limits (10^{-6}–10^{-4}), Rivers State sachet water produced comparatively higher lifetime exposure risks than the other packaged drinking water categories as shown in Table 3.8.

Table 3.8 Incremental Lifetime Cancer Risk (ILCR) of Endocrine-Disrupting Chemicals

Water Type	Adult ILCR	Child ILCR	Risk Interpretation
Rivers Bottled	5.81×10^{-6}	8.94×10^{-6}	Acceptable
Rivers Sachet	1.34×10^{-5}	2.08×10^{-5}	Acceptable but Elevated
Bayelsa Bottled	3.84×10^{-6}	6.12×10^{-6}	Acceptable
Bayelsa Sachet	8.96×10^{-6}	1.46×10^{-5}	Acceptable

3.9 Correlation Between Endocrine-Disrupting Chemicals in Packaged Drinking Water

Pearson correlation analysis demonstrated strong positive relationships among several endocrine-disrupting chemicals, indicating possible common contamination sources. The strongest positive correlation was observed between DBP and DEHP (r = 0.912), followed by BPA and DBP (r = 0.845). Moderate positive correlations were also observed between BPA and DEHP, suggesting that plastic packaging materials may represent a common source of chemical migration into packaged drinking water as shown in Table 3.9.

Table 3.9 Pearson Correlation Matrix for Endocrine-Disrupting Chemicals

Variable	BPA	DEP	DBP	DEHP	NP	OP
BPA	1.000	0.684	0.845	0.791	0.538	0.412
DEP	0.684	1.000	0.742	0.703	0.446	0.384
DBP	0.845	0.742	1.000	0.912	0.561	0.432
DEHP	0.791	0.703	0.912	1.000	0.584	0.446
NP	0.538	0.446	0.561	0.584	1.000	0.726
OP	0.412	0.384	0.432	0.446	0.726	1.000

3.10 Principal Contaminants Contributing to Human Health Risk

Risk contribution analysis demonstrated that DEHP accounted for the largest proportion of the cumulative human health risk in both Rivers and Bayelsa States, contributing 42.8% of the total Hazard Index, followed by DBP (28.6%) and BPA (14.2%). Nonylphenol, diethyl phthalate and octylphenol collectively contributed less than 15% of the cumulative health risk. The contribution pattern was similar in both study states but was consistently higher in Rivers State than in Bayelsa State, particularly for sachet drinking water as shown in Table 3.10.

Table 3.10 Percentage Contribution of Individual Endocrine-Disrupting Chemicals to Total Health Risk

Chemical	Contribution (%)
DEHP	42.8
DBP	28.6
BPA	14.2
DEP	5.4
NP	5.0
OP	4.0

3.11 Principal Component Analysis of Endocrine-Disrupting Chemicals in Packaged Drinking Water

Principal Component Analysis (PCA) extracted two principal components with eigenvalues greater than one, accounting for 81.6% of the total variance. Principal Component 1 explained 56.8% of the variance and was strongly associated with BPA, DBP and DEHP, suggesting contamination originating from plastic packaging materials and manufacturing processes. Principal Component 2 explained 24.8% of the total variance and was dominated by nonylphenol and octylphenol, indicating possible contributions from industrial discharges and environmental contamination during water production, storage and distribution. The PCA results demonstrate that plastic packaging and environmental pollution constitute the major sources of endocrine-disrupting chemicals in packaged drinking water marketed in Rivers and Bayelsa States as shown in Table 3.11.

Table 3.11 Principal Component Analysis of Endocrine-Disrupting Chemicals

Variable	PC1	PC2	Communality
BPA	0.894	0.214	0.845
DEP	0.762	0.381	0.726
DBP	0.923	0.184	0.886
DEHP	0.946	0.158	0.920
NP	0.382	0.884	0.927
OP	0.266	0.901	0.882

Eigenvalue: PC1 = 3.41; PC2 = 1.49
Variance Explained (%): PC1 = 56.8; PC2 = 24.8
Cumulative Variance (%): 81.6

3.12 Hierarchical Cluster Analysis of Sampling Locations

Hierarchical Cluster Analysis grouped the sampled packaged drinking water into three distinct clusters according to endocrine-disrupting chemical concentrations. Cluster I comprised bottled water samples from Yenagoa, Amassoma and Sagbama, which exhibited the lowest contaminant concentrations. Cluster II consisted mainly of bottled water from Port Harcourt and Obio/Akpor together with sachet water from Bayelsa State, reflecting moderate contamination levels. Cluster III included sachet water samples from Port Harcourt, Eleme and Bonny, characterised by the highest concentrations of BPA, DBP and DEHP and representing the greatest potential human health concern as shown in Table 3.12.

Table 3.12 Hierarchical Cluster Analysis of Sampling Locations

Cluster	Sampling Locations	Contamination Level
Cluster I	Yenagoa (Bottled), Amassoma (Bottled), Sagbama (Bottled), Ogbia (Bottled)	Low
Cluster II	Port Harcourt (Bottled), Obio/Akpor (Bottled), Yenagoa (Sachet), Amassoma (Sachet), Ogbia (Sachet)	Moderate
Cluster III	Port Harcourt (Sachet), Eleme (Sachet), Bonny (Sachet), Obio/Akpor (Sachet)	High

3.13 Human Health Risk Classification According to Sampling Location

Human health risk classification revealed marked geographical differences in exposure to endocrine-disrupting chemicals. All bottled drinking water samples from Bayelsa State were classified as low risk, whereas sachet water from Port Harcourt, Eleme and Bonny was classified as high risk, particularly for children. Moderate risk was observed among sachet water samples obtained from Yenagoa, Ogbia and Sagbama. Rivers State recorded a greater proportion of high-risk packaged drinking water than Bayelsa State as shown in Table 3.13.

Table 3.13 Human Health Risk Classification According to Sampling Location

Sampling Location	Water Type	Adult Risk	Child Risk
Port Harcourt	Bottled	Moderate	Moderate
Port Harcourt	Sachet	High	High
Obio/Akpor	Bottled	Moderate	Moderate
Obio/Akpor	Sachet	High	High
Eleme	Sachet	High	High
Bonny	Sachet	High	High
Yenagoa	Bottled	Low	Low
Yenagoa	Sachet	Moderate	Moderate
Amassoma	Bottled	Low	Low
Amassoma	Sachet	Moderate	Moderate
Ogbia	Bottled	Low	Low
Ogbia	Sachet	Moderate	Moderate
Sagbama	Bottled	Low	Low

3.14 Descriptive Statistics of Endocrine-Disrupting Chemicals

Descriptive statistical analysis demonstrated substantial variability in endocrine-disrupting chemical concentrations among packaged drinking water samples. DEHP recorded the highest mean concentration (1.24 ± 0.39 μg/L) and the greatest variability, whereas octylphenol exhibited the lowest mean concentration (0.18 ± 0.07 μg/L). The relatively high coefficients of variation observed for BPA, DBP and DEHP indicate considerable differences among packaged drinking water brands and sampling locations in Rivers and Bayelsa States as shown in Table 3.14.

Table 3.14 Descriptive Statistics of Endocrine-Disrupting Chemicals (μg/L)

Chemical	Minimum	Maximum	Mean ± SD	Coefficient of Variation (%)
BPA	0.18	1.08	0.61 ± 0.21	34.4
DEP	0.12	0.84	0.51 ± 0.18	35.3
DBP	0.28	1.62	0.97 ± 0.31	32.0
DEHP	0.42	2.08	1.24 ± 0.39	31.5
NP	0.10	0.72	0.41 ± 0.14	34.1
OP	0.04	0.36	0.18 ± 0.07	38.9

3.15 Comparative Human Exposure to Endocrine-Disrupting Chemicals Between Rivers and Bayelsa States

Comparative analysis showed that residents consuming packaged drinking water from Rivers State experienced significantly greater exposure to endocrine-disrupting chemicals than those in Bayelsa State. Mean cumulative exposure indices for BPA, DBP and DEHP were approximately 28–36% higher in Rivers State than in Bayelsa State. The observed differences were more pronounced among consumers of sachet drinking water than bottled water, indicating that packaging quality and environmental conditions may influence chemical migration into drinking water as shown in Table 3.15.

Table 3.15 Comparative Human Exposure Indices

Exposure Parameter	Rivers State	Bayelsa State	p-value
Mean EDI (μg/kg/day)	0.148 ± 0.032	0.109 ± 0.024	<0.001
Mean CDI (μg/kg/day)	0.135 ± 0.028	0.098 ± 0.021	<0.001
Mean Hazard Index	0.80 ± 0.18	0.61 ± 0.15	0.002
Mean ILCR	9.62×10^{-6}	6.48×10^{-6}	0.005

4.0 Discussion

The widespread detection of endocrine-disrupting chemicals in packaged drinking water indicates that contamination was not restricted to a particular water type or geographical area. DEHP showed the highest overall detection frequency of 91.3%, followed by DBP at 85.0% and BPA at 76.3%. This pattern reflects the extensive use of DEHP and DBP as plasticisers in packaging materials, production tubing, seals and associated water-processing equipment. Cao [8] identified phthalates as common contaminants of foods and beverages because they are physically incorporated rather than covalently bound to polymer structures. The present detection pattern is also consistent with the global evidence reviewed by Luo et al. [21], who found that trace phthalates frequently occurred in bottled water and were influenced by manufacturing and storage conditions.

The higher detection frequencies observed in sachet water than bottled water suggest that packaging composition and production quality influenced contaminant migration. Sachet water is commonly packaged in thin, flexible polymer films that may contain additives capable of migrating into water, particularly under warm storage conditions. Abbasi et al. [1] reported that the migration of endocrine-disrupting chemicals from food-contact materials is controlled by polymer type, temperature, contact duration and chemical properties. Fasano et al. [13] similarly demonstrated that phthalates, alkylphenols and bisphenol A could migrate from packaging into food simulants. The elevated tropical temperatures experienced during roadside display and transportation in Rivers and Bayelsa States may therefore have promoted greater migration into sachet water.

The mean concentrations of BPA, DEP, DBP, DEHP, NP and OP were consistently higher in sachet water from Rivers State than in the other packaged water categories. DEHP recorded the highest mean concentration, reaching 1.68 ± 0.24 μg/L in Rivers State sachet water, compared with 1.12 ± 0.19 μg/L in Rivers bottled water, 0.82 ± 0.15 μg/L in Bayelsa bottled water and 1.34 ± 0.20 μg/L in Bayelsa sachet water. The predominance of DEHP agrees with findings from bottled-water investigations in which high-molecular-weight phthalates were among the major detected compounds [4, 10]. Farhadi et al. [12] also identified DEHP as a frequently reported phthalate in drinking water across the Western Pacific region, although concentrations varied widely according to analytical method, packaging and storage conditions.

DBP concentrations ranged from 0.64 ± 0.10 μg/L in Bayelsa bottled water to 1.26 ± 0.18 μg/L in Rivers sachet water. The higher concentrations in sachet water support the possibility of direct migration from packaging films or contamination during production. Edjere et al. [10] reported phthalate esters in bottled water brands marketed in Delta State and attributed variations among brands to differences in source water, packaging, and storage. Taiwo et al. [31] similarly demonstrated substantial variations in phthalate concentrations among beverages marketed in Lagos and Ogun States, reinforcing the importance of production practices and container composition in determining consumer exposure.

BPA concentrations were also higher in Rivers sachet water, with a mean value of 0.84 ± 0.13 μg/L, compared with 0.39 ± 0.08 μg/L in Bayelsa bottled water. Although polyethylene sachets are not traditionally associated with high BPA content, contamination may arise from processing equipment, storage containers, recycled polymers, or source water. Abbasi et al. [1] emphasised that endocrine-disrupting chemicals may migrate from several food-contact materials rather than from the final consumer package alone. The detection of BPA in both bottled and sachet water therefore suggests that contamination may have occurred at multiple stages of production and distribution.

The occurrence of nonylphenol and octylphenol at lower concentrations than the phthalates may reflect their different sources and physicochemical characteristics. These alkylphenols are commonly associated with industrial surfactants, detergents and cleaning formulations rather than their deliberate use as major plasticisers. Amiridou and Voutsa [5] detected alkylphenols in bottled water and suggested contributions from source-water contamination and packaging-related processes. The positive correlation between NP and OP in the present study supports a related source, potentially involving cleaning agents, industrial wastewater or contaminated production water.

The comparatively higher endocrine-disrupting chemical concentrations recorded in Rivers State may be associated with greater urbanisation, industrial activity, plastic waste generation and petroleum-related operations. Rivers State contains densely populated commercial centres and extensive industrial infrastructure, which may increase the environmental burden of plastic-associated chemicals.

Although studies 24 and 25 investigated different environmental contaminants, they similarly demonstrated the relevance of cumulative chemical exposure and health-risk assessment in Niger Delta communities [24, 25]. Environmental contamination of source water may therefore have combined with packaging migration to produce the geographical differences observed.

Comparison with the selected guideline values showed that BPA, DEP, NP and OP remained within the adopted limits, whereas DBP and DEHP exceeded or approached the reference values in some sachet-water categories. The DEHP concentration of 1.68 μg/L in Rivers sachet water exceeded the selected 1.00 μg/L benchmark, while Bayelsa sachet water contained 1.34 μg/L. Although regulatory values for many endocrine-disrupting chemicals in drinking water remain inconsistent, Dueñas-Moreno et al. [9] cautioned that current guidelines may not fully reflect contemporary evidence concerning low-dose exposure and mixture effects. EFSA [11] has also highlighted the need to consider cumulative exposure to phthalates with common reproductive and developmental endpoints. The strong positive correlation between DBP and DEHP ($r = 0.912$) indicates that both chemicals likely originated from similar packaging or processing sources. BPA also correlated strongly with DBP ($r = 0.845$), suggesting that brands or locations with elevated plastic-associated contamination tended to contain multiple endocrine-disrupting chemicals simultaneously. Iannone et al. [19] identified phthalates as a major quality-control issue in the beverage industry because contamination may arise from raw materials, plastic components, and production environments. Guart et al. [15] further showed that plasticisers can migrate from water pipes, demonstrating that contamination pathways extend beyond bottles and sachets.

The exposure assessment showed that children received higher estimated daily and chronic daily intakes than adults. For Rivers sachet water, the child EDI for DEHP reached 6.40×10^{-2} μg/kg/day, compared with an adult value of 4.80×10^{-2} μg/kg/day. This difference reflects the greater volume of water consumed relative to body weight among children. Heudorf et al. [18] noted that children represent a sensitive population for phthalate exposure because developmental processes may be affected by endocrine-active substances. Schettler [28] similarly emphasised that exposure through consumer products may begin early in life and occur through several concurrent pathways.

Individual hazard quotient values remained below unity, indicating that no single endocrine-disrupting chemical was expected to produce an appreciable non-carcinogenic effect under the exposure assumptions used. Nevertheless, DEHP produced the highest hazard quotient, reaching 0.727 in Rivers sachet water, followed by DBP at 0.327. These values identify DEHP and DBP as the principal risk-driving chemicals in the packaged-water samples. Their dominance is consistent with the risk-contribution analysis, in which DEHP accounted for 42.8% and DBP for 28.6% of the total estimated risk. Similar risk patterns have been reported in Nigerian bottled water and beverage studies where higher-molecular-weight phthalates contributed substantially to cumulative exposure [10, 31].

The cumulative Hazard Index for children consuming Rivers sachet water reached 1.26, exceeding the conventional safety threshold of one. This indicates that combined exposure may be of concern even when individual hazard quotients remain below unity.

The finding reinforces the importance of mixture-based assessment because consumers are exposed to several endocrine-disrupting chemicals simultaneously. Dueñas-Moreno et al. [9] argued that risk assessments based only on individual compounds may underestimate real-world exposure, particularly where chemicals share endocrine or reproductive endpoints. The Bayelsa sachet-water child Hazard Index of 0.99 was also close to unity, suggesting limited additional safety margin.

The estimated incremental lifetime cancer risks ranged from 3.84×10^{-6} in Bayelsa bottled water to 2.08×10^{-5} among children consuming Rivers sachet water. These values fell within the commonly applied acceptable range of 10^{-6} to 10^{-4} but indicated comparatively higher lifetime risk for sachet-water consumers. Edjere et al. [10] similarly applied carcinogenic risk models to phthalates in bottled water from southern Nigeria and emphasised that values within the regulatory range still warrant monitoring where exposure is continuous. The present findings should therefore not be interpreted as an absence of risk, especially because packaged water represents only one of several possible dietary and environmental exposure pathways.

Principal Component Analysis separated the contaminants into two major source groups. BPA, DEP, DBP and DEHP loaded strongly on the first component, indicating a packaging and processing-related source, while NP and OP dominated the second component, suggesting inputs from detergents, surfactants or environmental contamination. This interpretation agrees with the source classifications described by Cao [8], Guart et al. [15] and Abbasi et al. [1]. The Hierarchical Cluster Analysis further grouped sachet water from Port Harcourt, Eleme and Bonny into the highest-contamination cluster, confirming the combined influence of packaging type and local environmental conditions.

Conclusion

This study demonstrated the widespread occurrence of endocrine-disrupting chemicals in bottled and sachet drinking water marketed in Rivers and Bayelsa States, with phthalates and bisphenol A being the predominant contaminants. Sachet drinking water, particularly samples obtained from Rivers State, consistently recorded higher concentrations of endocrine-disrupting chemicals than bottled water, suggesting greater chemical migration from packaging materials and possible environmental contamination during production, storage and distribution. The observed geographical variation further indicates that the degree of urbanisation and industrial activities within the Niger Delta may influence the occurrence and distribution of these contaminants in packaged drinking water.

Human health risk assessment revealed that children experienced greater exposure than adults, with higher estimated daily intake, chronic daily intake and cumulative Hazard Index values. Although most carcinogenic risk estimates remained within internationally acceptable limits, the Hazard Index for children consuming sachet drinking water from Rivers State exceeded the recommended safety threshold, indicating the possibility of adverse non-carcinogenic health effects following prolonged exposure. Principal Component Analysis and Hierarchical Cluster Analysis further identified plastic packaging materials and environmental pollution as the principal contributors to endocrine-disrupting chemical contamination.

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