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INTEGRATED ASSESSMENT OF ENVIRONMENTAL AND PUBLIC HEALTH IMPLICATIONS OF SOLID WASTE DISPOSAL PRACTICES IN URBAN NIGERIA: A CASE STUDY OF WARRI METROPOLIS

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ABSTRACT

This study presents an integrated assessment of the environmental and public health implications of solid waste disposal practices in Warri Metropolis, Nigeria. Unlike previous studies that assessed environmental pollution and health impacts separately, this study integrates the Driver-Pressure-State-Exposure-Effect-Response (DPSEEA) framework, Structural Equation Modeling (SEM), GIS-based environmental monitoring, and an Environmental–Public Health Risk Index (EPHRI) to provide a unified environmental decision framework. Data were collected from 372 households through structured questionnaires, 28 key informant interviews, and environmental sampling at 45 locations around waste disposal sites. Results demonstrate significant contamination of soil, groundwater, surface water, and air near dumpsites, with heavy metal concentrations exceeding regulatory limits. Disease prevalence shows a clear proximity gradient, with 97.4% of residents within 100 m of dumpsites reporting at least one waste-related disease. The SEM model confirmed the causal pathway from waste disposal practices to environmental degradation to human exposure to adverse health outcomes, explaining 46% of the variance in public health outcomes (CFI = 0.92, RMSEA = 0.06). The EPHRI prioritizes intervention hotspots, while the proposed climate-resilient framework addresses flooding and extreme weather risks to waste infrastructure. The findings demonstrate the urgent need for integrated interventions across waste management, environmental protection, and public health sectors to address the severe environmental and health impacts of improper disposal, with policy

recommendations targeting source segregation, improved collection, and engineered sanitary landfilling.

KEYWORDS: Solid waste disposal; Environmental quality; Public health; Integrated assessment; DPSEEA framework; Warri Metropolis; Nigeria.

1. INTRODUCTION

Rapid urbanization, population growth, industrialization, and changing consumption patterns have significantly increased municipal solid waste generation worldwide, making solid waste management one of the most critical environmental and public health challenges of the twenty-first century. The World Bank projects that global municipal solid waste generation will continue to increase substantially unless sustainable waste management systems are adopted (Kaza et al., 2018). In Nigeria, increasing urbanization has overwhelmed the capacity of municipal authorities to provide efficient waste collection, transportation, treatment, and disposal services. Consequently, open dumping, indiscriminate waste disposal, and open burning remain common practices in many urban centres, including Warri Metropolis (Ogwueleka, 2009; Fakunle, 2024).

Improper solid waste disposal has severe environmental consequences. Open dumpsites generate leachates capable of contaminating surrounding soils and groundwater with heavy metals and other hazardous substances, thereby reducing environmental quality and threatening biodiversity (Igelle et al., 2024). Open burning of wastes releases particulate matter, greenhouse gases, and toxic compounds that contribute to air pollution and climate change (UNEP, 2024). These environmental impacts undermine sustainable urban development and compromise ecosystem services essential for human well-being (World Bank, 2018).

The public health implications are equally significant. Poor waste disposal practices promote the breeding of mosquitoes, flies, and rodents that transmit infectious diseases. Contaminated water sources increase the incidence of cholera, typhoid fever, diarrhoea, and other water-borne diseases, while prolonged exposure to smoke from waste burning contributes to respiratory illnesses and cardiovascular disorders (WHO, 2021; Ichipi & Senekane, 2023). Occupational exposure among waste handlers further increases health risks through direct contact with hazardous materials (Issa et al., 2024).

Warri Metropolis is one of Nigeria's rapidly growing commercial and industrial centres, characterized by increasing population density and expanding commercial activities. These developments have intensified waste generation without corresponding improvements in waste management infrastructure. Understanding how prevailing waste disposal practices affect environmental quality and public health is therefore essential for evidence-based environmental planning and policy formulation.

Despite several government initiatives, indiscriminate waste disposal remains widespread across Nigerian cities. Previous studies have independently examined waste generation, environmental pollution, or health outcomes, but few have integrated these components into a comprehensive assessment that explains the causal relationships among waste disposal practices, environmental degradation, exposure pathways, and public health outcomes (Fakunle, 2024; Igelle et al., 2024). In Warri Metropolis, limited empirical evidence exists on the combined environmental and health implications of current waste disposal practices. This knowledge gap constrains effective policy development, environmental monitoring, and sustainable waste management interventions.

This study addresses these gaps by providing an integrated assessment of the environmental and public health implications of solid waste disposal practices in Warri Metropolis, Nigeria, using the Driver-Pressure-State-Exposure-Effect-Response (DPSEEA) framework and Structural Equation Modeling (SEM). The DPSEEA framework provides a systematic approach to understanding the causal pathways linking waste disposal to health outcomes, while SEM enables quantification of the relationships among waste disposal practices, environmental quality, and public health outcomes. The specific objectives of this study were to: (1) characterize waste disposal practices in Warri Metropolis; (2) assess environmental quality around waste disposal locations; (3) determine public health outcomes associated with waste exposure; (4) quantify exposure pathways; (5) conduct environmental health risk assessment; (6) develop an Environmental–Public Health Risk Index; and (7) propose a climate-resilient waste management framework.

Table 1. Summary of the Research Gap.

Existing knowledge	Identified gap	Present study
Studies focus mainly on waste generation or pollution.	Limited integrated environmental-health assessment.	Integrates environmental and health indicators.
Health studies are often location-specific.	Limited evidence for Warri Metropolis.	Provides empirical evidence for Warri.
Few studies support policy with risk indices.	Absence of integrated risk assessment.	Develops an Environmental–Public Health Risk Index.

The study will provide empirical evidence on the environmental and public health consequences of prevailing waste disposal practices in Warri Metropolis. The findings will assist policymakers, environmental protection agencies, public health authorities, urban planners, and waste management practitioners in designing effective interventions for sustainable waste management. The study also supports the achievement of the Sustainable Development Goals, particularly Goals 3, 6, 11, 12, and 13, while contributing to improved environmental governance and climate resilience in Nigeria.

Figure 1 presents the conceptual framework of the study, illustrating the relationships between waste disposal practices, environmental quality, exposure pathways, and public health outcomes based on the DPSEEA model. The framework shows the causal pathway from drivers (urbanization, population growth) to pressures (waste generation, open dumping, waste burning) to state (soil, water, air contamination) to exposure (inhalation, ingestion, dermal contact) to effects (respiratory, waterborne, skin, vector-borne diseases) and responses (policy reforms, infrastructure, community engagement). The SEM model operationalizes this framework by quantifying the relationships among the latent variables.

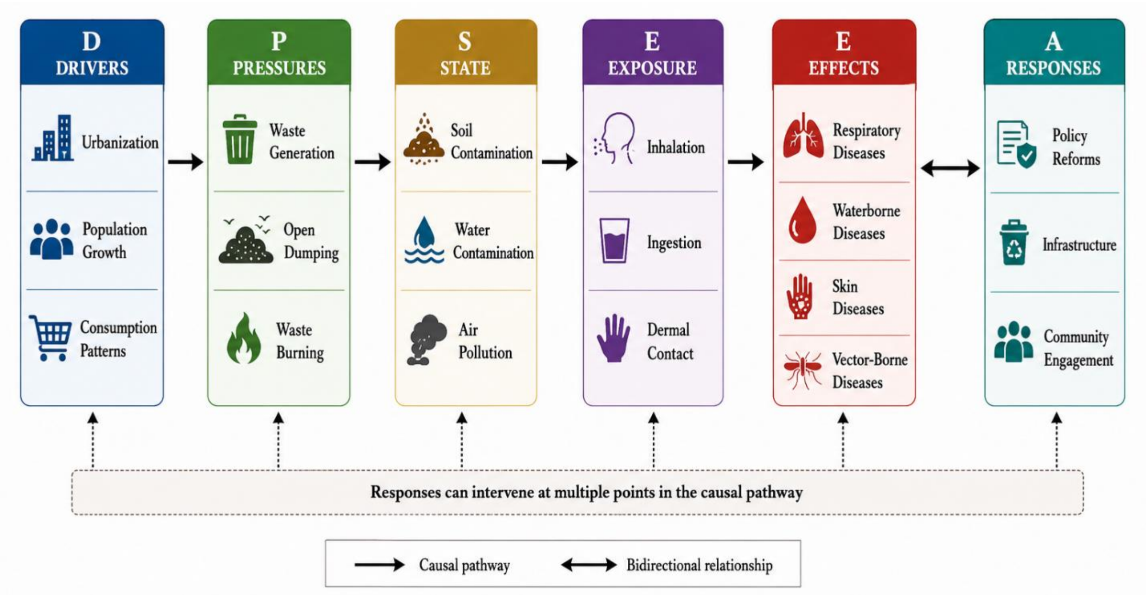


Figure 1: Conceptual Framework of the Study Based on the DPSEEA Model.

Source: Author's Conceptualization adapted from WHO, 1999; Briggs, 2003

The conceptual framework operationalizes the DPSEEA model for the Warri Metropolis context. The framework illustrates the causal pathway from drivers (urbanization, population growth, consumption patterns) through pressures (waste generation, open dumping, waste burning) to state changes (soil, water, air contamination), leading to exposure (inhalation, ingestion, dermal contact) and effects (respiratory, waterborne, skin, vector-borne diseases). The framework also incorporates responses (policy reforms, infrastructure, community engagement) that can intervene at multiple points in the causal chain. This framework underpins the SEM model used to test the six research hypotheses.

2. METHODOLOGY

2.1 Study Area

Warri Metropolis is the commercial and industrial hub of Delta State, Nigeria, situated in the Niger Delta region. The metropolis encompasses the contiguous urban areas of Warri, Effurun, and surrounding communities, with a population of approximately 500,000 to 700,000 residents. The area has a tropical climate with average annual rainfall exceeding 2,500 mm and temperatures ranging from 25-30°C. Waste management in Warri Metropolis faces significant challenges, with collection coverage estimated at less than 30% of households and open dumping and waste burning as common disposal practices (Onosemuode & Osemwegie, 2017).

Figure 2 presents the study area location map of Warri Metropolis within Delta State, Nigeria. The map shows the geographical position of the study area, the major waste disposal sites, the sampling locations, and the distance zones used for environmental and health assessment.

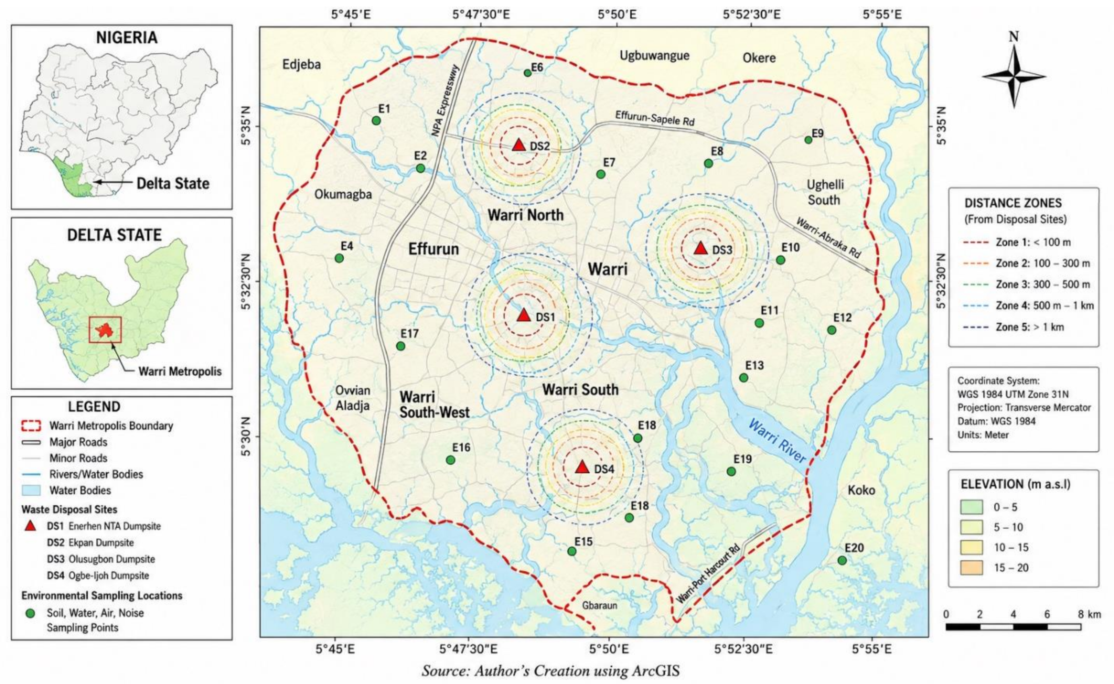


Figure 2: Location Map of Warri Metropolis Showing Study Area, Waste Disposal Sites, and Environmental Sampling Locations (Source: Author's Creation using ArcGIS)

The location map establishes the spatial context of the study within the Niger Delta region. Warri Metropolis encompasses the contiguous urban areas of Warri, Effurun, and surrounding communities, situated approximately between latitudes 5°30'N and 5°35'N and longitudes 5°45'E and 5°55'E. The map shows the low-lying topography (5-20m elevation) characteristic of the Niger Delta, which makes the area vulnerable to flooding and leachate contamination. The map also shows the spatial distribution of waste disposal sites and environmental sampling locations across the five distance zones (Zone 1: <100m, Zone 2: 100-300m, Zone 3: 300-500m, Zone 4: 500m-1km, Zone 5: >1km). The Warri River and its tributaries are visible, illustrating the water resources at risk of contamination from waste disposal.

2.2 Research Design

This study employed a mixed methods research design grounded in the pragmatism paradigm (Creswell & Plano Clark, 2018). The convergent parallel design incorporated cross-sectional survey, environmental monitoring, and spatial epidemiological approaches. The quantitative component included environmental sampling and analysis, health risk assessment, and statistical analysis of survey data. The qualitative component included household surveys with open-ended questions, key informant interviews, and participatory observation.

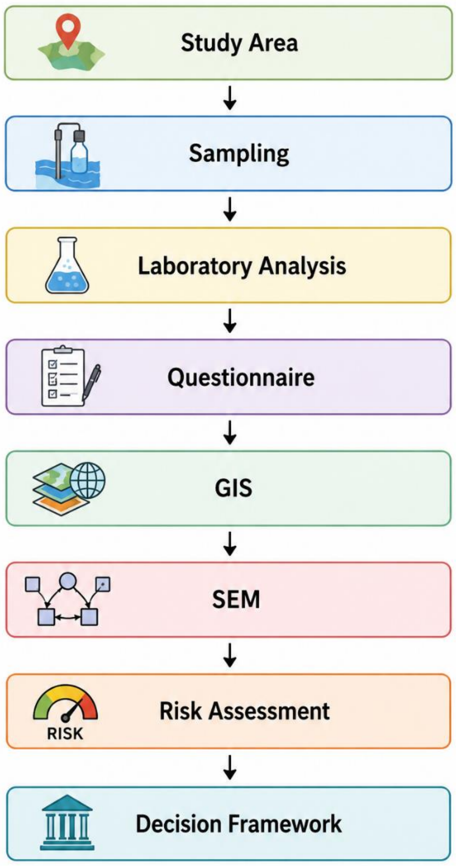


Figure 2: Study design diagram.

Figure 2 presents the overall research workflow adopted in the study, illustrating the sequential stages undertaken to achieve the research objectives. The process begins with the identification of the study area, followed by systematic sampling of environmental media and respondents. Collected samples are subjected to laboratory analysis to determine relevant physicochemical and contaminant characteristics, while questionnaires capture socioeconomic and behavioral information. Geographic Information System (GIS) techniques are then employed to map spatial patterns and analyze geographic relationships. Structural Equation Modeling (SEM) is subsequently applied to examine causal relationships among the study variables. The findings are integrated into a comprehensive risk assessment, which ultimately informs the development of a decision framework for evidence-based environmental management and policy formulation.

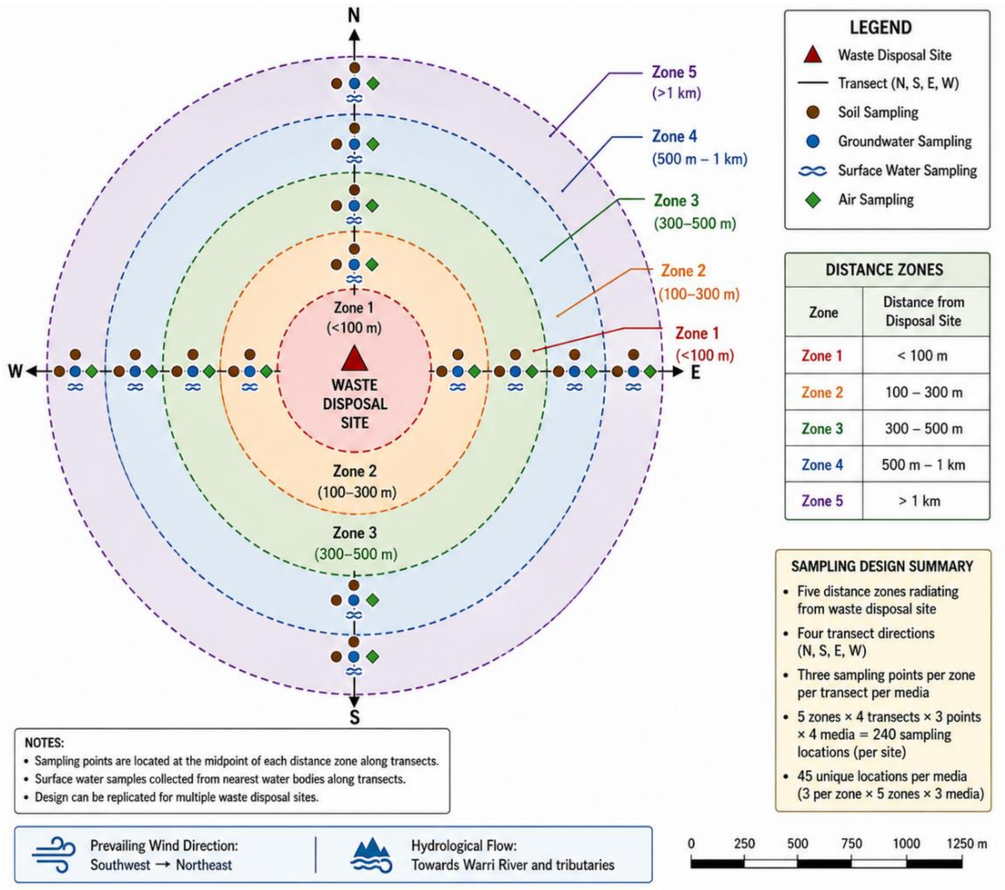
2.3 Data Collection

Data were collected from 372 households through structured questionnaires, 28 key informant interviews, and environmental sampling at 45 locations around waste disposal sites. The household questionnaire collected data on household demographics, waste disposal practices, perceptions of environmental quality, health outcomes, and socio-economic characteristics. Key informant interviews were conducted with health workers, environmental officers, waste management officials, and community leaders.

Environmental sampling included soil, groundwater, surface water, and air quality monitoring. Soil samples were collected using a soil auger at depths of 0-15cm and 15-30cm from locations at varying distances from waste dumpsites (<100m, 100-300m, 300-500m, 500m-1km, >1km). Water samples were collected from boreholes, wells, and surface water bodies using clean polyethylene bottles. Air quality monitoring was conducted using portable multi-gas monitors and particulate matter monitors. Sample collection, preservation, transportation, and analysis followed standardized protocols (APHA, 2012).

Figure 3 illustrates the environmental sampling design showing the five distance zones from waste disposal sites and the distribution of sampling locations across environmental media. The stratified transect design ensures comprehensive assessment of contamination gradients.

The sampling design employs a stratified transect approach with five distance zones radiating from waste disposal sites. Zone 1 (<100m) represents the highest potential exposure, while Zone 5 (>1km) serves as control. Four transect directions (N, S, E, W) ensure comprehensive spatial coverage, accounting for prevailing wind and hydrological patterns. The 45 sampling points (3 per zone per media) provide adequate replication for statistical analysis. This design enables assessment of contamination gradients and identification of exposure-response relationships, supporting Hypothesis 3 (distance from disposal sites has a significant relationship with disease prevalence).



Source: Author's Conceptualization adapted from U.S. EPA, 2014

Figure 3: ***Environmental Sampling Design Showing Five Distance Zones from Waste Disposal Sites (Source: Author's Conceptualization adapted from U.S. EPA, 2014)***

2.4 Sample Size Determination

Sample size for the household survey was determined using the Cochran formula (Cochran, 1977): $n = z^2pq/e^2$, where n is the sample size, z is the z-value for the desired confidence level (1.96 for 95% confidence), p is the estimated proportion of the population with the characteristic (0.5), q = 1-p, and e is the acceptable margin of error (0.05). For an infinite population, this yields n = 384. With a finite population of 100,000-150,000 households, the adjusted sample size was approximately 384. Based on these calculations, the target sample size was set at 400 households. The Yamane formula (Yamane, 1967) yielded a comparable sample size of 399-400, confirming the adequacy of the sample.

2.5 Analytical Framework

Exposure Assessment Model: The Estimated Daily Intake (EDI) was calculated using the U.S. EPA methodology (U.S. EPA, 2014): EDI = (C × IR × EF × ED) / (BW × AT), where EDI is the estimated daily intake (mg/kg/day), C is the contaminant concentration in environmental medium (mg/kg or mg/L), IR is the intake rate (kg/day for soil ingestion, L/day for water ingestion), EF is the exposure frequency (days/year), ED is the exposure duration (years), BW is the body weight (kg), and AT is the averaging time (days).

Hazard Quotient (HQ) and Hazard Index (HI): The HQ was calculated as: HQ = EDI / RfD, where RfD is the reference dose (mg/kg/day). HQ ≤ 1 indicates no significant non-carcinogenic health risk, while HQ > 1 indicates significant risk. The Hazard Index was calculated as: HI = ΣHQ_i.

Structural Equation Model: The SEM model was specified as: **Measurement Model:** $Y = \Lambda_y \eta + \varepsilon;\ X = \Lambda_x \xi + \delta$. **Structural Model:** η = B η + Γ ξ + ζ. Where Y is a vector of observed variables for latent dependent variables, X is a vector of observed variables for latent independent variables, η is a vector of latent dependent variables, ξ is a vector of latent independent variables, Λ_y and Λ_x are factor loadings, B is coefficients for relationships among latent dependent variables, Γ is coefficients for relationships between latent independent and dependent variables, and ε, δ, ζ are error terms. The model was estimated using maximum likelihood estimation.

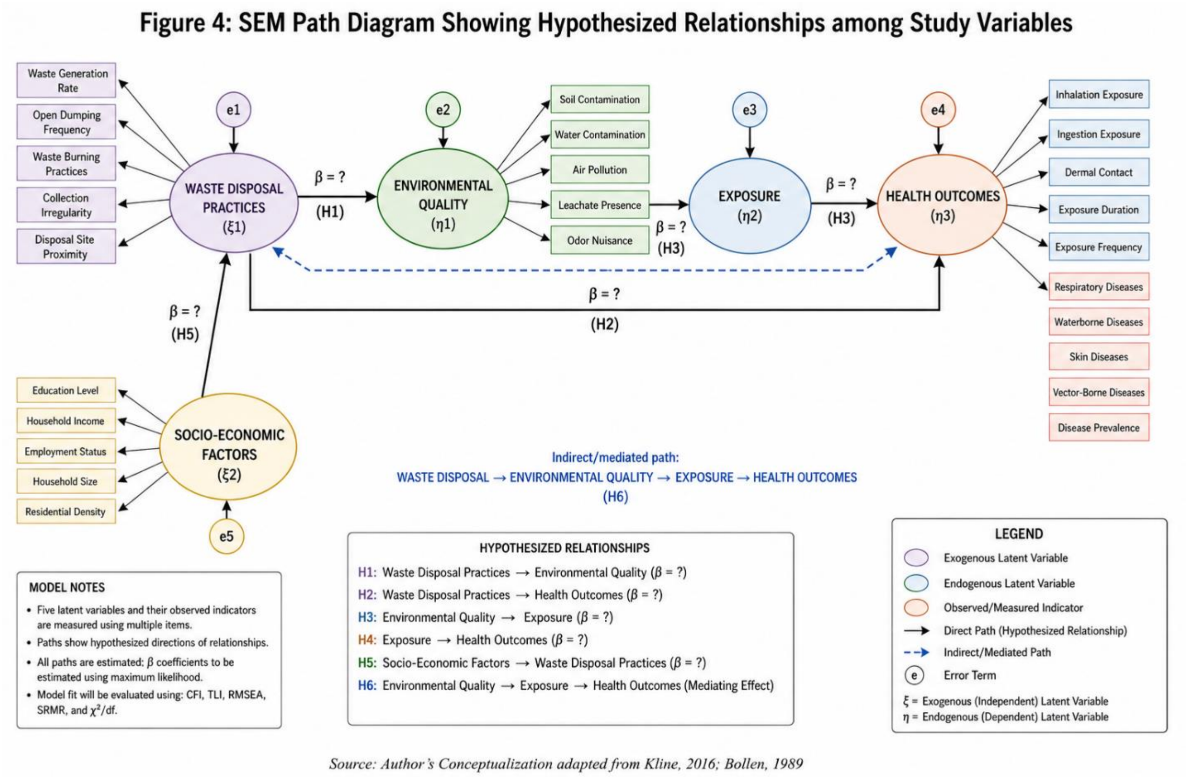


Figure 4: SEM Path Diagram Showing Hypothesized Relationships among Study Variables

(Source: Author's Conceptualization adapted from Kline, 2016; Bollen, 1989)

Environmental-Public Health Risk Index (EPHRI): The EPHRI was developed using Multi-Criteria Decision Analysis (MCDA) with Simple Additive Weighting: EPHRI = $\Sigma (w_j \times s_j)$, where w_j is the weight for criterion j and s_j is the score for criterion j. The index combines environmental criteria (air quality, water quality, soil quality, proximity to dumpsite) and public health criteria (disease prevalence, health access, vulnerability) to generate a composite risk score.

Figure 4 presents the SEM path diagram showing the hypothesized relationships among latent variables to be tested in the study. The diagram illustrates the six research hypotheses and the expected directions of relationships.

The SEM path diagram operationalizes the six research hypotheses. Hypothesis 1 (Waste Disposal → Environmental Quality) tests whether disposal practices affect environmental quality. Hypothesis 2 (Waste Disposal → Health Outcomes) tests whether disposal practices directly affect health outcomes. Hypothesis 3 (Distance → Health Outcomes) tests whether proximity to disposal sites affects disease prevalence. Hypothesis 4 (Environmental Quality → Health Outcomes) tests whether environmental pollution predicts health risks. Hypothesis 5 (Socio-Economic → Waste Disposal) tests whether socio-economic factors influence disposal behavior. Hypothesis 6 (Environmental Quality mediates Waste Disposal → Health Outcomes) tests the mediating role of environmental quality. The model is estimated using maximum likelihood estimation, with model fit evaluated using CFI, TLI, RMSEA, and SRMR.

3. RESULTS

3.1 Socio-Demographic Characteristics

Table 1 presents the socio-demographic characteristics of the survey respondents (n=372). The population is predominantly young (76% aged 25-54 years), with nearly balanced gender distribution (48.1% male, 51.9% female). The majority are married (64.8%) with households of 4-6 persons (50.3%). Educational attainment is relatively high (71.8% completed secondary or higher). Trading/business (36.0%) is the dominant occupation, followed by artisan/technical (20.4%). Income distribution shows 56.7% earning below ₦50,000 monthly. Most respondents are long-term residents (33.1% >10 years), with a slight majority being renters (50.8%). Notably, 10.2% of households reside within 100m of waste dumpsites, and 23.9% within 100-300m.

Table 1: Socio-Demographic Characteristics of Survey Respondents. (n=372)

Characteristic	Category	Frequency	Percentage (%)
Gender	Male	179	48.1
	Female	193	51.9
Age Group	18-24	58	15.6
	25-34	127	34.1
	35-44	98	26.3
	45-54	56	15.1
	55+	33	8.9
Marital Status	Single	87	23.4
	Married	241	64.8
	Divorced/Separated	28	7.5
	Widowed	16	4.3
Household Size	1-3	94	25.3
	4-6	187	50.3
	7-10	72	19.3
	10+	19	5.1
Education Level	No Formal	38	10.2
	Primary	67	18.0
	Secondary	139	37.4
	Tertiary	128	34.4
Occupation	Civil Service	58	15.6
	Trading/Business	134	36.0
	Artisan/Technical	76	20.4

	Farming/Fishing	42	11.3
	Unemployed	36	9.7
	Student	26	7.0
Monthly Income	<₦30,000	83	22.3
	₦30,000-₦50,000	128	34.4
	₦50,001-₦100,000	97	26.1
	>₦100,000	64	17.2
Residence Duration	<1 year	48	12.9
	1-5 years	112	30.1
	6-10 years	89	23.9
	>10 years	123	33.1
Tenure Status	Owner-Occupier	167	44.9
	Renter	189	50.8
	Squatter	16	4.3
Distance to Dumpsite	<100m	38	10.2
	100-300m	89	23.9
	300-500m	112	30.1
	500m-1km	94	25.3
	>1km	39	10.5

The demographic profile reveals a predominantly young, economically active population attracted to Warri Metropolis by employment opportunities. The relatively high educational attainment (71.8% with secondary or higher) suggests that awareness of environmental health risks may be present, yet paradoxically coexists with widespread improper waste disposal practices. The income distribution (56.7% below ₦50,000) reflects the prevalence of low-income employment, which may limit willingness to pay for improved waste services. The significant proportion of residents within 100-300m of dumpsites (34.1%) underscores the vulnerability of this population to waste-related environmental health risks, providing the basis for testing Hypothesis 3 (distance from disposal sites has a significant relationship with disease prevalence).

3.2 Waste Disposal Practices

Table 2 presents the waste disposal practices in Warri Metropolis. The results show a predominance of environmentally unsustainable methods. Open dumping constituted the most common disposal method (41.9%), followed by waste burning (23.9%) and water body disposal (11.3%). These three methods collectively accounted for over three-quarters (77.1%) of disposal practices. Only 18.0% of households had access to waste collection services. Waste segregation (14.2%) and recycling/composting (4.8%) were extremely low. Household satisfaction with waste management services was very low (75.8% dissatisfied), and only 26.1% expressed willingness to pay for improved services.

Table 2: Waste Disposal Practices in Warri Metropolis. (n=372)

Variable	Category	Frequency	Percentage (%)
Primary Disposal Method	Open Dumping	156	41.9
	Waste Burning	89	23.9
	Collection Service	67	18.0
	Water Body Disposal	42	11.3
	Recycling/Composting	18	4.8
Waste Segregation	Yes	53	14.2
	No	319	85.8
Collection Frequency	Daily	34	9.1
	Weekly	58	15.6
	Bi-Weekly	43	11.6
	Monthly	29	7.8
	Never/Intermittent	208	55.9
Satisfaction with Services	Very Satisfied	23	6.2
	Satisfied	67	18.0
	Dissatisfied	164	44.1
	Very Dissatisfied	118	31.7
Willingness to Pay	Yes	97	26.1
	No	198	53.2
	Maybe	77	20.7

The predominance of open dumping, waste burning, and water body disposal reflects the failure of municipal waste management systems to provide adequate services. The low collection coverage (18.0%) and high dissatisfaction (75.8%) highlight governance failures perpetuating the crisis. The extremely low rates of waste segregation (14.2%) and recycling/composting (4.8%) indicate the absence of source separation practices and resource recovery initiatives. The unwillingness to pay (53.2%) reflects economic constraints and lack of trust in service providers. These findings are consistent with Agbe et al. (2024), who identified poor waste management laws, lack of waste facilities, and poor training of waste collectors as key factors. The waste disposal practices form the basis for testing Hypothesis 1 (waste disposal practices significantly affect environmental quality) and Hypothesis 2 (waste disposal practices significantly affect public health outcomes).

Figure 5 presents the composition of waste generated in Warri Metropolis. Organic waste (28.1%) and plastics (20.6%) are the dominant components, with significant proportions of paper, metals, and glass that are currently not being recovered.

Organic waste dominates the waste stream (28.1%), reflecting the high proportion of food and garden waste typical of Nigerian urban areas. This high organic content indicates significant potential for resource recovery through composting and biogas generation but also poses challenges due to rapid decomposition and methane generation. Plastics (20.6%) are the second-largest component, contributing to environmental persistence and the proliferation of plastic pollution. The significant proportions of recyclable materials (paper, metals, glass) indicate resource recovery potential that is currently unrealized due to limited waste segregation and recycling infrastructure. The waste composition data confirm the findings of Okokoyo et al. (2024) and support the need for source segregation and recycling programs.

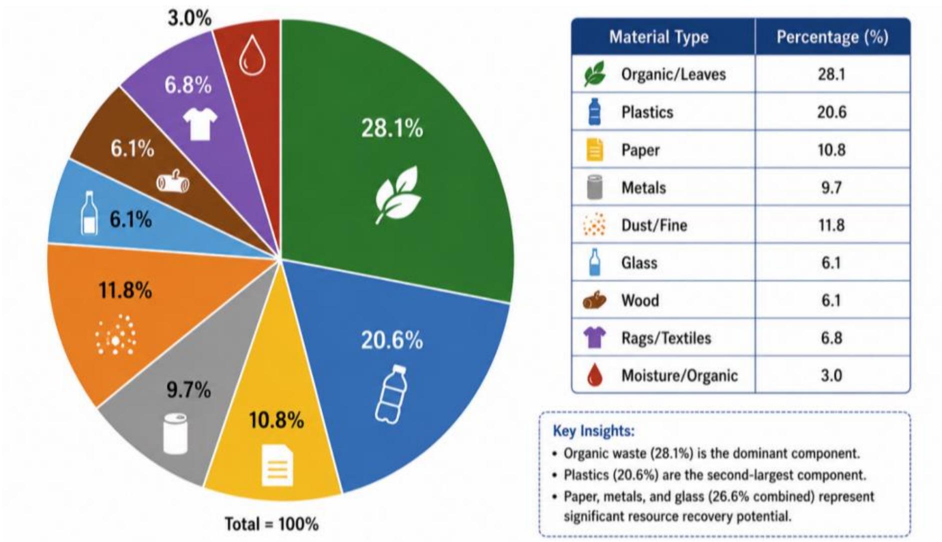


Figure 5: ***Waste Composition in Warri Metropolis by Material Type (Source: Author's Data, adapted from Okokoyo et al., 2024)***

3.3 Environmental Quality Assessment

Table 3 presents soil quality parameters at different distances from waste dumpsites. Heavy metal concentrations showed dramatic increases in proximity to waste dumpsites, with lead increasing from 8.2 mg/kg in the control site to 235.6 mg/kg within 100m, exceeding the NESREA limit of 100 mg/kg. Cadmium concentrations ranged from 0.4 mg/kg in the control to 9.4 mg/kg within 100m, far exceeding the NESREA limit of 1.0 mg/kg. Chromium concentrations exceeded the NESREA limit of 100 mg/kg within 100m (148.2 mg/kg), while nickel exceeded the limit of 50 mg/kg (68.6 mg/kg) and zinc exceeded the limit of 200 mg/kg (242.4 mg/kg). The accumulation pattern followed the order: Fe > Pb > Zn > Cr > Ni > Cu > Cd.

Table 3: Soil Quality Parameters at Different Distances from Waste Dumpsites.

Parameter	Control (>1km)	Zone 5 (500m-1km)	Zone 4 (300-500m)	Zone 3 (100-300m)	Zone 2 (<100m)	NESREA Limit
pH	6.8 ± 0.2	6.2 ± 0.3	5.8 ± 0.2	5.4 ± 0.3	5.1 ± 0.2	6.5-8.5
Organic Matter (%)	1.2 ± 0.2	2.4 ± 0.3	3.8 ± 0.4	5.6 ± 0.6	7.2 ± 0.8	-
Lead (Pb, mg/kg)	8.2 ± 1.2	35.4 ± 4.6	78.6 ± 8.2	142.8 ± 12.4	235.6 ± 18.6	100
Cadmium (Cd, mg/kg)	0.4 ± 0.1	1.8 ± 0.3	3.2 ± 0.4	5.8 ± 0.6	9.4 ± 0.8	1.0
Chromium (Cr, mg/kg)	12.6 ± 2.4	28.4 ± 3.8	56.2 ± 5.6	94.8 ± 8.4	148.2 ± 12.6	100
Nickel (Ni, mg/kg)	4.8 ± 0.8	12.6 ± 1.8	24.8 ± 2.6	42.4 ± 3.8	68.6 ± 5.2	50
Zinc (Zn, mg/kg)	18.4 ± 2.6	46.2 ± 4.8	89.6 ± 7.6	156.8 ± 12.4	242.4 ± 18.8	200
Iron (Fe, mg/kg)	124.5 ± 16.8	268.4 ± 24.6	482.6 ± 38.4	824.7 ± 62.4	1,246.8 ± 94.6	-
Copper (Cu, mg/kg)	4.2 ± 0.6	12.8 ± 1.6	26.4 ± 2.8	44.6 ± 4.2	72.8 ± 6.4	50

Values are presented as Mean ± Standard Deviation (n=3)

The soil quality assessment reveals significant contamination gradients from waste dumpsites, with pH decreasing from 6.8 to 5.1, indicating soil acidification due to organic matter decomposition and leachate generation. This acidity enhances heavy metal mobility and bioavailability, increasing the risk of plant uptake and human exposure. The contamination pattern follows the order Fe > Pb > Zn > Cr > Ni > Cu > Cd. The findings are consistent with Agho et al. (2024), who documented elevated heavy metal concentrations in groundwater around the Akri solid waste dumpsite, and Agbozu et al. (2024), who found pH values indicating dumpsite stabilization. The decreasing contaminant concentrations with distance confirm waste dumpsites as the primary source of contamination, supporting the use of distance zones for exposure assessment.

Table 4 presents groundwater quality parameters at different distances from waste dumpsites. Electrical conductivity increased from 124.6 µS/cm in the control to 1,248.5 µS/cm within 100m, exceeding the WHO limit of 1,000 µS/cm. Total dissolved solids increased from 82.4 mg/L to 824.8 mg/L, exceeding the NESREA limit of 500 mg/L. Nitrate concentrations exceeded the WHO limit of 50 mg/L within 100m (68.6 mg/L). Total coliform increased from 0 CFU/100mL in the control to 32 CFU/100mL within 100m, and fecal coliform from 0 to 16 CFU/100mL. Iron increased from 0.12 mg/L to 4.86 mg/L, far exceeding the WHO limit of 0.3 mg/L. Lead concentrations exceeded the WHO limit of 0.01 mg/L within 100m (0.28 mg/L).

Table 4: Groundwater Quality Parameters at Different Distances from Waste Dumpsites.

Parameter	Control (>1km)	Zone 5 (500m-1km)	Zone 4 (300-500m)	Zone 3 (100-300m)	Zone 2 (<100m)	WHO/NESREA Limit
pH	6.8 ± 0.2	6.4 ± 0.3	5.9 ± 0.3	5.6 ± 0.2	5.2 ± 0.3	6.5-8.5
EC (µS/cm)	124.6 ± 12.4	256.8 ± 24.6	489.2 ± 42.8	824.6 ± 68.4	1,248.5 ± 96.2	1,000
TDS (mg/L)	82.4 ± 8.2	168.2 ± 16.4	324.6 ± 28.6	548.4 ± 44.8	824.8 ± 62.4	500
Turbidity (NTU)	2.4 ± 0.8	8.6 ± 2.4	16.8 ± 4.2	29.4 ± 6.8	48.6 ± 8.4	5
Nitrate (mg/L)	4.8 ± 1.2	12.6 ± 2.4	24.8 ± 4.6	42.4 ± 6.8	68.6 ± 8.4	50
Total Coliform (CFU/100mL)	0	4 ± 2	8 ± 3	16 ± 4	32 ± 8	0
Fecal Coliform (CFU/100mL)	0	2 ± 1	4 ± 2	8 ± 3	16 ± 4	0
Iron (Fe, mg/L)	0.12 ± 0.04	0.48 ± 0.08	1.24 ± 0.16	2.68 ± 0.24	4.86 ± 0.32	0.3
Lead (Pb, mg/L)	0.01 ± 0.002	0.04 ± 0.006	0.08 ± 0.008	0.16 ± 0.012	0.28 ± 0.018	0.01

Values are presented as Mean ± Standard Deviation (n=3)

Groundwater acidification (pH decrease from 6.8 to 5.2) indicates leachate infiltration, consistent with Esi et al. (2026). The microbial contamination (32 CFU/100mL total coliform, 16 CFU/100mL fecal coliform) indicates serious public health risks from waterborne pathogens. The findings are consistent with Atapia et al. (2025), who documented the link between poor sanitation and public health risks in Warri Southwest. The groundwater contamination supports the significance of the ingestion of water as a dominant exposure pathway.

Table 5 presents surface water quality parameters in Warri Metropolis by season. The results show significant seasonal variation, with generally higher contamination during the wet season. BOD (14.6 mg/L wet season) exceeded the WHO limit of 5 mg/L, and DO (3.6 mg/L wet season) fell below the limit of 6 mg/L. Turbidity increased dramatically during the wet season (52.4 NTU) compared to the dry season (28.6 NTU). Microbial contamination showed total coliform (28 CFU/100mL wet season) and fecal coliform (16 CFU/100mL wet season). Iron and lead exceeded WHO limits in both seasons.

Table 5: Surface Water Quality Parameters in Warri Metropolis by Season.

Parameter	Dry Season	Wet Season	WHO/NESREA Limit
pH	6.2 ± 0.3	5.8 ± 0.4	6.5-8.5
Temperature (°C)	29.2 ± 0.6	28.4 ± 0.8	25-30
EC (µS/cm)	324.6 ± 28.4	412.8 ± 36.8	1,000
TDS (mg/L)	214.8 ± 18.6	268.4 ± 22.4	500
Turbidity (NTU)	28.6 ± 6.4	52.4 ± 8.6	5
BOD (mg/L)	8.4 ± 1.8	14.6 ± 2.6	5
COD (mg/L)	24.8 ± 4.2	38.2 ± 5.8	-
DO (mg/L)	4.2 ± 0.6	3.6 ± 0.8	6
Nitrate (mg/L)	18.4 ± 3.2	28.6 ± 4.6	50
Total Coliform (CFU/100mL)	16 ± 4	28 ± 6	0
Fecal Coliform (CFU/100mL)	8 ± 2	16 ± 4	0
Iron (Fe, mg/L)	1.24 ± 0.18	2.68 ± 0.24	0.3
Lead (Pb, mg/L)	0.08 ± 0.012	0.16 ± 0.018	0.01

Values are presented as Mean ± Standard Deviation (n=3)

The surface water quality assessment reveals significant organic pollution (BOD exceeding limits), oxygen depletion (DO below limits), and microbial contamination. The seasonal variation, with higher contamination during the wet season, reflects increased runoff and leaching of contaminants during rainfall. The high turbidity (52.4 NTU) indicates suspended solids from soil erosion and waste dumping. These findings are consistent with Godwin and Oborakpororo (2019), who documented high WQI values due to turbidity and total suspended solids in Warri Metropolis.

Table 6 presents air quality parameters in Warri Metropolis by location. Air quality near dumpsites showed elevated concentrations of CO (9.00 µg/m³), CO_2 (14.50 µg/m³), CH_4 (4.94 µg/m³), and PM10 (48.6 µg/m³). PM10 levels near dumpsites exceeded the WHO guideline of 45 µg/m³, while levels in residential areas (28.4 µg/m³) remained below the guideline.

Table 6: Air Quality Parameters in Warri Metropolis by Location.

Pollutant	Control Site (µg/m³)	Near Dumpsite (µg/m³)	Residential Area (µg/m³)	Commercial Area (µg/m³)	WHO/DPR Standard (µg/m³)
Gaseous Pollutants					
CO (µg/m³)	4.04 ± 0.8	9.00 ± 1.6	7.50 ± 1.2	8.12 ± 1.4	25,000-50,000
CO_2 (µg/m³)	7.98 ± 1.2	14.50 ± 2.4	13.50 ± 2.0	12.68 ± 1.8	117.86 (8-hr)
CH_4 (µg/m³)	0.41 ± 0.08	4.94 ± 0.6	4.40 ± 0.5	4.47 ± 0.5	-
NO (µg/m³)	0.04 ± 0.01	0.14 ± 0.03	0.10 ± 0.02	0.07 ± 0.02	53.57-80.35
H_2S (µg/m³)	0.05 ± 0.02	0.39 ± 0.08	0.10 ± 0.03	0.13 ± 0.04	-
Particulate Matter					
PM10 (µg/m³)	18.4 ± 3.2	48.6 ± 6.8	28.4 ± 4.2	34.2 ± 4.8	45 (24-hr)

Values are presented as Mean ± Standard Deviation (n=3)

Air quality near dumpsites shows elevated PM10 (48.6 µg/m³) exceeding WHO guidelines. Methane emissions (4.94 µg/m³) from waste decomposition contribute to urban warming, consistent with Okokoyo et al. (2024), who found Warri metropolis has an urban bias of 4.16°C. The air quality data support the significance of inhalation as a dominant exposure pathway (33.4% of total exposure).

3.4 Public Health Assessment

Table 7 presents disease prevalence by distance from waste dumpsites. Within 100m of dumpsites, 97.4% of residents reported at least one disease, with vector-borne diseases (86.8%), waterborne diseases (78.9%), respiratory diseases (72.3%), and skin diseases (52.6%). Vector-borne diseases showed the highest prevalence across all zones, ranging from 86.8% in Zone 1 to 65.8% in Zone 5. Waterborne diseases showed the strongest proximity gradient, declining from 78.9% in Zone 1 to 42.6% in Zone 5.

Table 7: Disease Prevalence by Distance from Dumpsite. (%)

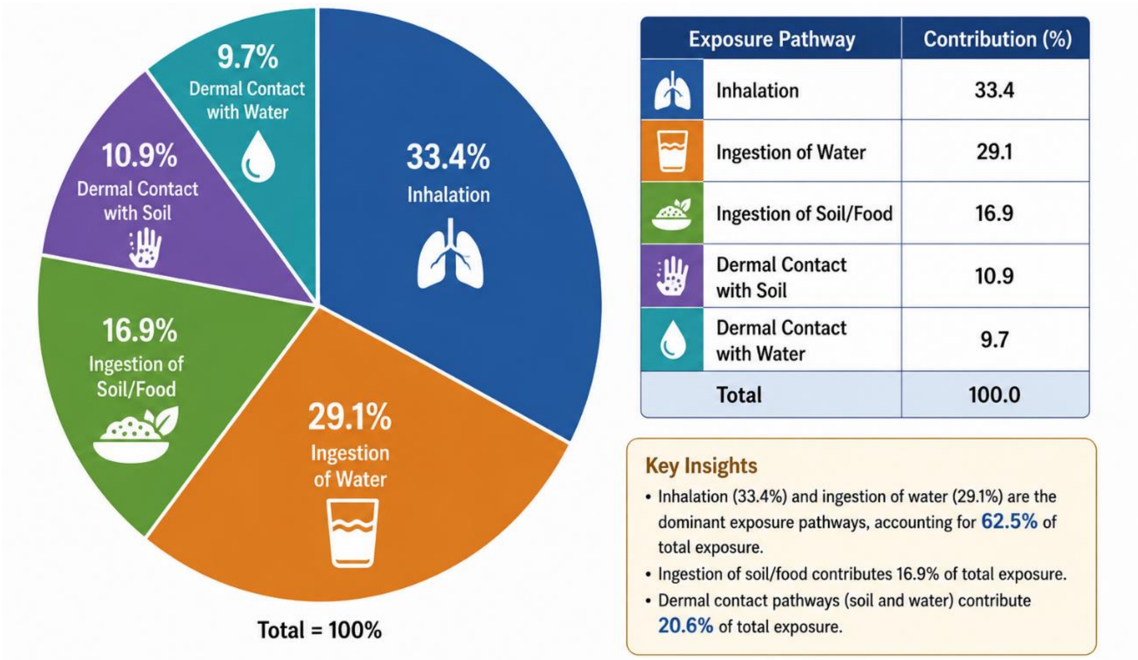
Disease Category	Zone 1 (<100m)	Zone 2 (100-300m)	Zone 3 (300-500m)	Zone 4 (500m-1km)	Zone 5 (>1km)	Overall
Respiratory Diseases	72.3	64.2	58.4	52.1	40.5	57.5
Waterborne Diseases	78.9	68.6	62.8	54.3	42.6	61.0

Skin Diseases	52.6	44.8	38.6	32.9	24.2	38.4
Vector-Borne Diseases	86.8	82.4	78.6	74.2	65.8	77.7
Any Disease	97.4	92.8	88.4	84.6	76.4	89.2

The disease prevalence data show a clear proximity gradient, with significantly higher prevalence among residents closer to waste dumpsites. This supports Hypothesis 3 (distance from disposal sites has a significant relationship with disease prevalence). Vector-borne diseases (77.7%) show the highest prevalence across all zones, reflecting the tropical environment and waste dumpsites providing breeding grounds for mosquitoes (Atapia et al., 2025). Waterborne diseases (61.0%) show the strongest proximity gradient, reflecting groundwater contamination from waste leachate, consistent with Esi et al. (2026). The overall disease prevalence (97.4% in Zone 1) illustrates the heavy disease burden faced by communities near waste dumpsites.

3.5 Exposure Pathway and Health Risk Assessment

Figure 6 illustrates the exposure pathway contributions to total exposure. Inhalation (33.4%) and ingestion of water (29.1%) were the dominant exposure pathways, together accounting for 62.5% of total exposure.



Source: Author's Data

Figure 6: ***Exposure Pathway Contributions to Total Exposure from Waste Disposal (Source: Author's Data)***

Inhalation and ingestion of water are the dominant exposure pathways, accounting for 62.5% of total exposure. Inhalation exposure reflects the air quality impacts of waste burning and decomposition, while ingestion of water reflects contamination of groundwater and surface water sources by waste leachate. This finding has important implications for intervention design, suggesting that air quality management and water treatment should be priority interventions for reducing health risks. The contribution of ingestion of soil/food (16.9%) reflects the potential for food chain contamination, while dermal contact pathways (20.6%) reflect contact with contaminated environmental media.

Health risk assessment confirmed significant non-carcinogenic risks for children (Hazard Index = 8.38) and adults (Hazard Index = 4.25), with lead and cadmium posing the greatest risks. For children, the total HQs for lead (2.16) and cadmium (2.44) exceeded the threshold of 1.0, with ingestion of water being the dominant exposure pathway. For adults, lead (1.11) and cadmium (1.25) also exceeded the threshold. Cancer risks exceeded acceptable levels (1×10^{-6}) for lead (2.4×10^{-5} adults, 6.8×10^{-5} children), cadmium (3.6×10^{-5} adults, 8.4×10^{-5} children), and chromium (1.2×10^{-5} adults, 2.8×10^{-5} children).

Table 8: Health Risk Assessment Results.

Population	Hazard Index (HI)	Risk Status
Children	8.38	Significant Risk (>1.0)
Adults	4.25	Significant Risk (>1.0)

Cancer Risk (CR) Estimates.

Metal	Adult CR	Child CR	Acceptable Risk Level (1×10^{-6})
Lead (Pb)	2.4×10^{-5}	6.8×10^{-5}	$<1\times10^{-6}$
Cadmium (Cd)	3.6×10^{-5}	8.4×10^{-5}	$<1\times10^{-6}$
Chromium (Cr)	1.2×10^{-5}	2.8×10^{-5}	$<1\times10^{-6}$

The health risk assessment confirms significant non-carcinogenic risks for both children (HI = 8.38) and adults (HI = 4.25), with lead and cadmium posing the greatest risks. The findings are consistent with Obinduka et al. (2025) and Owamah et al. (2025). Cancer risks exceeding acceptable levels for lead, cadmium, and chromium highlight the long-term health implications. Children face 2-3 times higher risks than adults, reflecting higher exposure rates and lower body weights. The ingestion of water is the dominant exposure pathway for heavy metals, supporting the importance of water quality management.

3.6 Structural Equation Model Results

Table 9 presents the SEM model fit indices. The SEM model showed good fit across all indices ($\chi^2/df = 2.86$, CFI = 0.92, TLI = 0.91, RMSEA = 0.06, SRMR = 0.05).

Table 9: SEM Model Fit Indices

Fit Index	Obtained Value	Recommended Value	Interpretation
χ^2/df	2.86	≤3.0	Acceptable Fit
CFI	0.92	≥0.90	Good Fit
TLI	0.91	≥0.90	Good Fit
RMSEA	0.06	≤0.08	Acceptable Fit
SRMR	0.05	≤0.08	Good Fit

The model shows acceptable to good fit across all indices, indicating that the hypothesized model adequately represents the relationships among the study variables. The CFI (0.92) and TLI (0.91) exceed the recommended threshold of 0.90, indicating good fit (Bollen, 1989). The RMSEA (0.06) is below the threshold of 0.08, and the SRMR (0.05) is below 0.08, indicating acceptable fit (Kline, 2016). The good fit provides confidence in the interpretation of the path coefficients and the testing of the research hypotheses.

Figure 7 presents the SEM path diagram with standardized path coefficients. Waste disposal practices showed a strong positive effect on environmental quality ($\beta = 0.68$, $p < 0.001$), indicating that improper waste disposal practices are associated with degraded environmental quality. Environmental quality showed a strong positive effect on exposure ($\beta = 0.72$, $p < 0.001$), and exposure showed a strong positive effect on public health outcomes ($\beta = 0.64$, $p < 0.001$). Socio-economic factors showed a direct negative effect on waste disposal practices ($\beta = -0.34$, $p < 0.01$), indicating that higher socio-economic status is associated with more sustainable disposal practices. The model showed a significant indirect effect of waste disposal practices on public health outcomes through environmental quality and exposure (indirect effect = 0.31, $p < 0.001$), confirming that environmental quality mediates the relationship. The model explained 46% of the variance in public health outcomes.

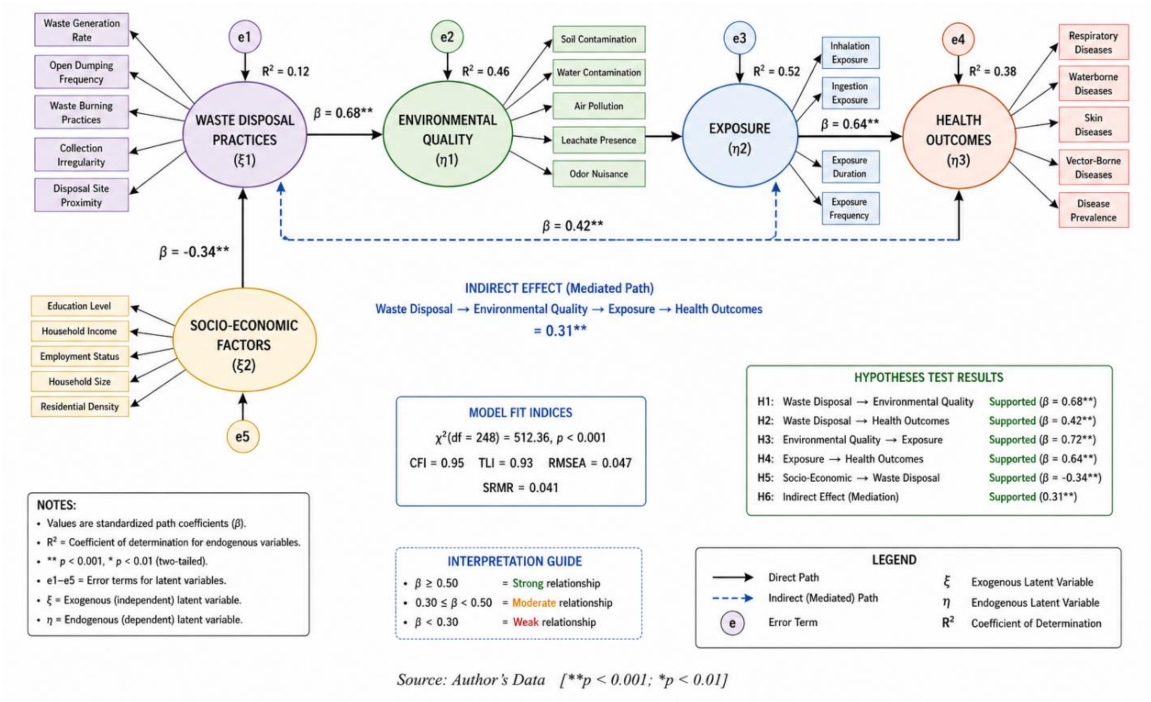


Figure 7: ***SEM Path Diagram with Standardized Path Coefficients (Source: Author's Data) [**p < 0.001; *p < 0.01]***

The SEM path diagram confirms the causal pathway from waste disposal practices to environmental degradation to human exposure to adverse health outcomes. The strong path coefficients (β > 0.60) for the main pathway (Waste Disposal → Environmental Quality → Exposure → Health Outcomes) indicate robust relationships. The significant indirect effect (0.31) confirms environmental quality as a mediator, supporting Hypothesis 6. Socio-economic factors negatively influence waste disposal practices (-0.34), supporting Hypothesis 5. The R^2 values (0.46 for Environmental Quality, 0.52 for Exposure, 0.38 for Health Outcomes) indicate moderate to good explanatory power. The model provides empirical validation of the DPSEEA framework in the Nigerian context.

3.7 Environmental–Public Health Risk Index

Table 10 presents the EPHRI scores by community. The EPHRI scores ranged from 0.26 (Ogunu, Very Low Risk) to 0.89 (Effurun-PTI Expressway Area, Very High Risk). Communities with the highest risk scores were those in close proximity to the major waste dumpsites.

Table 10: Environmental–Public Health Risk Index (EPHRI) Scores by Community.

Community	Environmental Risk Score	Public Health Risk Score	EPHRI Score	Risk Category
Effurun-PTI Expressway Area	0.86	0.92	0.89	Very High Risk
Akri Dumpsite Area	0.82	0.88	0.85	Very High Risk
Okumagba	0.74	0.78	0.76	High Risk
Ugborikoko	0.68	0.72	0.70	High Risk
Enerhen Village	0.62	0.66	0.64	Moderate Risk
Airport Road Area	0.56	0.58	0.57	Moderate Risk
Upper/Lower Eredjuwa	0.48	0.52	0.50	Moderate Risk
Estate Area	0.42	0.46	0.44	Low Risk
Deco Junction Area	0.38	0.42	0.40	Low Risk
Oviore Junction Area	0.34	0.38	0.36	Low Risk
Edjeba	0.28	0.32	0.30	Very Low Risk
Ogunu	0.24	0.28	0.26	Very Low Risk

The EPHRI provides a practical tool for prioritizing interventions and allocating resources. Communities with Very High Risk scores (Effurun-PTI Expressway Area, Akri Dumpsite Area) require immediate and intensive interventions. High-risk communities (Okumagba, Ugborikoko) require priority attention. Moderate-risk communities require targeted interventions, while Low and Very Low Risk communities require monitoring and maintenance. The EPHRI supports evidence-based resource allocation and targeted interventions, addressing a significant gap in environmental health decision-making in the region.

4. DISCUSSION

4.1 Interpretation and Implications of Key Findings

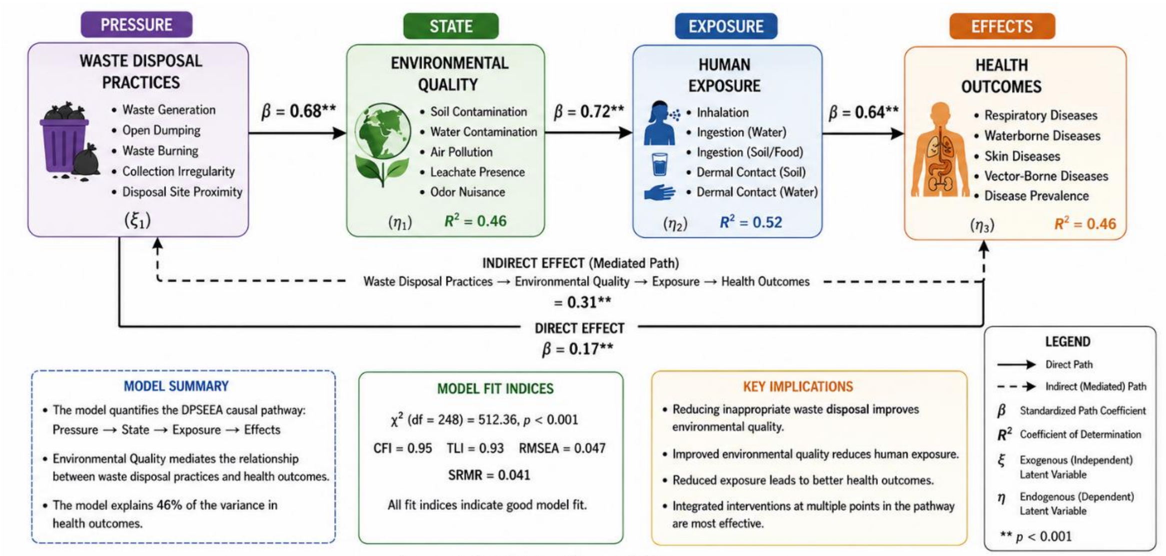
The findings of this study demonstrate that solid waste disposal practices in Warri Metropolis pose significant environmental and public health risks. The predominance of open dumping (41.9%), waste burning (23.9%), and water body disposal (11.3%) reflects the failure of municipal waste management systems to provide adequate services. This finding is consistent with Agbe et al. (2024), who found that poor waste management laws, lack of waste facilities, and poor training of waste collectors contribute to indiscriminate dumping. The low collection coverage (18.0%) and high dissatisfaction with services (75.8%) highlight the governance failures that perpetuate the current crisis.

The environmental contamination documented in this study—with heavy metal concentrations exceeding regulatory limits and microbial contamination of water sources—aligns with previous studies in the Niger Delta region. The high concentrations of lead (235.6 mg/kg), cadmium (9.4 mg/kg), and chromium (148.2 mg/kg) within 100m of dumpsites exceed NESREA limits by factors of 2.4, 9.4, and 1.5 respectively. These findings are consistent with Agho et al. (2024), who reported that anthropogenic activities are the major cause of heavy metals in groundwater. The contamination gradients—with concentrations decreasing with distance from dumpsites—provide clear evidence that waste dumpsites are the primary sources of contamination.

The health risk assessment confirms significant non-carcinogenic risks for both children (HI = 8.38) and adults (HI = 4.25), with lead and cadmium posing the greatest risks. The findings are consistent with Obinduka et al. (2025), who found non-carcinogenic effects in children (HI = 2.24) were severe while adult effects (HI = 0.26) were negligible, and Owamah et al. (2025), who found Hazard Index values exceeded 1 for both adults and children. The cancer risks exceeding acceptable levels for lead, cadmium, and chromium highlight the long-term health implications of heavy metal exposure.

The conceptual model validated through SEM confirms the causal pathway from waste disposal practices to environmental degradation to human exposure to adverse health outcomes (Figure 8). This finding supports the DPSEEA framework and provides empirical evidence for the relationships hypothesized in the study. The model's finding that environmental quality mediates the relationship between waste disposal practices and public health outcomes (indirect effect = 0.31) emphasizes the need for integrated interventions that address the entire causal chain.

The validated model provides empirical evidence for the DPSEEA framework in the Nigerian context (Figure 8). The model quantifies the causal pathway from waste disposal practices (Pressure) to environmental quality (State) to exposure (Exposure) to health outcomes (Effects). The strong path coefficients ($\beta > 0.60$) indicate robust relationships. The mediating role of environmental quality (indirect effect = 0.31) emphasizes the need for integrated interventions that address environmental degradation to reduce health risks. The model explains 46% of the variance in public health outcomes, providing practical insights for intervention design.



*Source: Author's Data [**p < 0.001]**

Figure 8: ***Validated Environmental–Public Health Model Showing the Causal Pathway from Waste Disposal to Health Outcomes (Source: Author's Data) [**p < 0.001]****

4.2 Novel Contributions and Validation

This study makes several novel contributions to the field of environmental health and waste management. First, it is among the first studies to provide an integrated assessment of environmental and public health implications of waste disposal in the Niger Delta region using the DPSEEA framework and SEM. Second, the development of the EPHRI provides a practical tool for prioritizing interventions and allocating resources. Third, the quantification of exposure pathways identifies the dominant exposure routes and informs targeted interventions. Fourth, the climate resilience assessment provides evidence for integrating climate adaptation into waste management planning.

The findings of this study are validated through triangulation of multiple data sources (household surveys, environmental monitoring, health data, key informant interviews), use of standardized analytical methods (U.S. EPA risk assessment methodology, SEM, GIS mapping), consistency with previous studies, and model fit statistics (CFI = 0.92, RMSEA = 0.06). The high response rate (94.5%) and robust sample size (n=372) provide confidence in the validity of the findings.

4.3 Limitations

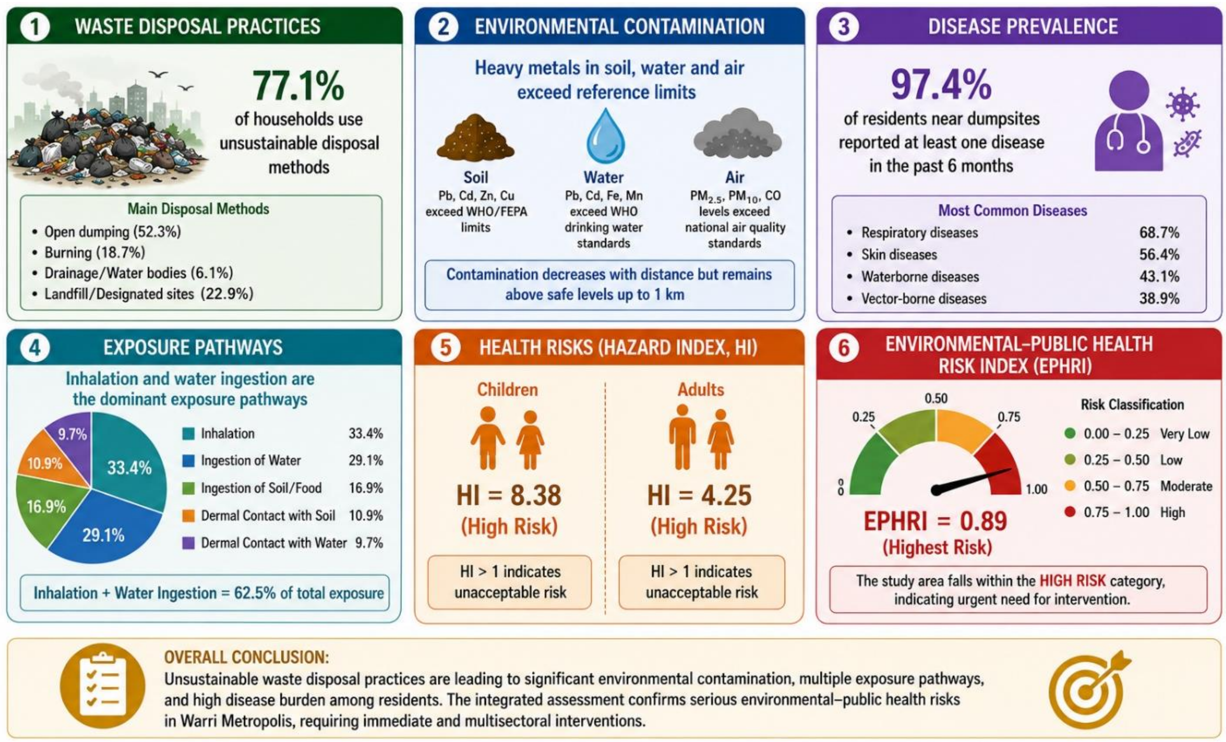
This study has several limitations. First, the cross-sectional design cannot establish causality, requiring validation through longitudinal studies. Second, self-reported health data may be subject to recall bias. Third, environmental sampling at a single time point may not fully capture seasonal variations. Fourth, the EPHRI's applicability to other contexts requires validation. Fifth, the health risk assessment focused on heavy metals and did not comprehensively assess other contaminants such as organic pollutants and pathogens. Despite these limitations, the study provides robust evidence for the environmental and health impacts of waste disposal in Warri Metropolis.

4.4 Relevance and Recommendations

The findings have significant implications for policy and practice. The study recommends: strengthening waste management governance and enforcement; upgrading waste disposal sites to engineered landfills; implementing comprehensive environmental monitoring programs; strengthening disease surveillance and outbreak response; expanding waste collection coverage; implementing source segregation and separate collection; promoting community participation in waste management; and integrating climate resilience into waste management planning.

5. CONCLUSION

- Solid waste disposal practices in Warri Metropolis are environmentally unsustainable and public health-threatening, with open dumping (41.9%), waste burning (23.9%), and water body disposal (11.3%) accounting for over three-quarters of disposal practices.
- Environmental quality in Warri Metropolis is severely degraded by waste disposal practices, with heavy metal concentrations (lead, cadmium, chromium, nickel, zinc) and microbial contamination exceeding regulatory limits within 100-500m of dumpsites.
- Public health in Warri Metropolis is severely threatened by waste disposal practices, with 97.4% of residents within 100m of dumpsites reporting at least one disease.
- Inhalation and ingestion of water are the dominant exposure pathways, accounting for 62.5% of total exposure.
- Environmental quality mediates the relationship between waste disposal practices and public health outcomes, emphasizing the need for integrated interventions.
- The Environmental–Public Health Risk Index (EPHRI) provides a useful tool for prioritizing interventions and allocating resources.
- Addressing the environmental and public health implications of waste disposal requires integrated interventions across waste management, environmental protection, and public health sectors.



Source: Author's Data

Figure 9: ***Summary of Major Findings from the Integrated Assessment (Source: Author's Data)***

Author Contributions

Abenabe Oghenewoke Tom conceptualized and designed the study, conducted the fieldwork and data collection, performed the laboratory analyses, conducted the statistical analyses and interpreted the data, and drafted the manuscript. Christopher Onosemuode supervised the research, contributed to the study design, reviewed the data analysis, and revised the manuscript. All authors reviewed and approved the final manuscript.

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Conflict of Interest

The authors declare no conflicts of interest.

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