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## Evaluation of Medical Wastes and Associated Environmental Impacts in Uyo Metropolis: A Comparative Study of Secondary and Tertiary Healthcare Facilities

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### Abstract


Medical waste management poses significant environmental and public health challenges in developing urban areas like Uyo metropolis, Nigeria, where inadequate disposal practices exacerbate contamination risks. This comparative study evaluates the generation, characterization, and environmental impacts of medical wastes from a secondary healthcare facility (St. Luke's Hospital, Anua) and a tertiary facility (University of Uyo Teaching Hospital), focusing on leachate composition, effects on plants and soil, groundwater quality, and air pollution. Employing a cross-sectional design, data were collected from June to December 2025, involving 240 samples (120 per facility) across waste streams, leachate, soil, plants, groundwater, and air. Waste characterization revealed the University of Uyo generating 3-4 times more waste (500-700 kg/day) with a higher hazardous fraction (48% against 35%), including elevated infectious (25% against 20%), sharps (8% against 5%), and pathological (10% against 5%) types. Leachate from the University of Uyo showed 1.5-3 times higher contaminants (BOD 400 mg/L against 250 mg/L; Pb 0.45 mg/L against 0.15 mg/L), exceeding World Health Organization (WHO) limits and indicating severe runoff risks in Uyo's rainy climate. Soil impacts were more pronounced at the University of Uyo, with higher metal accumulation (Pb 60 mg/kg against 25 mg/kg) leading to 30-40% plant growth inhibition (against 15-20%) and reduced microbial activity ( $8.0 \times 10^5$  CFU/g against  $1.5 \times 10^6$  CFU/g). Groundwater contamination was 2-3 times greater at the University of Uyo (Pb 0.30 mg/L against 0.10 mg/L), yielding an unsuitable Water Quality Index (WQI) (300 against 150, poor). Air emissions from incineration were 1.5-2 times higher at the University of Uyo (PM<sub>2.5</sub> 65  $\mu\text{g}/\text{m}^3$  against 40  $\mu\text{g}/\text{m}^3$ ), contributing to urban air quality degradation. Statistical analyses (t-tests,  $p < 0.05$ ; large effect sizes,  $d > 0.8$ ) confirmed significant disparities, attributing them to the University of Uyo's scale and complexity. Findings underscore the need for enhanced waste segregation, treatment infrastructure, and regulatory enforcement at tertiary facilities to mitigate environmental hazards, promoting sustainable healthcare practices in Nigeria's urban south.

**Keywords:** Medical wastes, Environmental impacts, Healthcare facilities, Waste management.

## 1 | Introduction

Waste can be considered an irrelevant or undesired material that is not useful at the point of generation, and therefore discarded. In recent times, rapid urbanization and population growth have intensified the rate of

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waste generation, leading to increased waste volumes in the society [1–4]. Medical waste, from facilities ranging from primary clinics to advanced tertiary hospitals encompassing infectious, pathological, pharmaceutical, chemical, and sharps materials generated from healthcare activities, represents a growing environmental and public health concern globally, particularly in resource-limited settings [5], [6]. Uyo metropolis, the capital of Akwa Ibom State in southeastern Nigeria, exemplifies this challenge with its dense population (>500,000) and tropical climate (annual rainfall 2,500 mm, temperatures 25-30°C), which facilitates pollutant migration through runoff and leaching. Improper management such as open dumping, inadequate incineration, and poor segregation results in contamination of soil, water, and air, posing risks like heavy metal bioaccumulation, pathogen spread, and respiratory ailments [7–9]. Secondary facilities like St. Luke's Hospital, Anua (150 beds, general care focus) generate simpler waste streams, while tertiary ones like University of Uyo Teaching Hospital (500 beds, specialized services including surgeries and diagnostics) produce more complex and voluminous wastes, amplifying environmental burdens. Globally, the World Health Organization (WHO) estimates that healthcare activities generate 0.5-2 kg of waste per bed daily, with 15-25% hazardous, contributing to environmental degradation if unmanaged. In Africa, studies in Ethiopia and South Africa highlight leachate from medical dumpsites exceeding safe limits for BOD, COD, and heavy metals, leading to groundwater pollution and ecosystem disruption [10], [11]. Nigerian research, such as in Lagos and Abuja, reports similar issues: tertiary hospitals generate up to 4 times more hazardous waste than secondary ones, with leachate Pb levels 10-50 times above WHO thresholds (0.01 mg/L), correlating with soil acidification and reduced crop yields. In Uyo, local studies indicate air pollution from incinerators elevating PM<sub>2.5</sub> to 50-100 µg/m<sup>3</sup>, exceeding WHO's 15 µg/m<sup>3</sup> limit, and groundwater coliforms reaching 1,000 CFU/100mL in hospital vicinities. However, comparative analyses between secondary and tertiary facilities are scarce, particularly integrating multi-media impacts (soil, plants, water, air) with statistical rigor. Gaps include seasonal variability in tropical regions, where monsoons enhance leachate percolation, and the lack of site-specific data for policy formulation [12], [13]. This study addresses these by quantifying disparities, revealing tertiary facilities' disproportionate contributions (2-3x higher contaminants) and advocating for context-specific interventions. The rationale stems from Uyo's vulnerability: shallow aquifers (10 m water table), agricultural dependence, and flood-prone topography heighten exposure risks, potentially affecting food security and health in nearby communities. By comparing St. Luke's and the University of Uyo, this research reveals scale-related impacts, informing scalable solutions like improved incinerators or recycling programs [14], [15] with the objectives, which include characterizing waste generation and composition, analyzing leachate, soil/plant, groundwater, and air contaminants, statistically interpreting differences and recommending mitigation strategies. Grounded in Nigerian Environmental Standards and Regulations Enforcement Agency (NESREA) and WHO guidelines, the study promotes sustainable waste management, aligning with Nigeria's National Environmental Policy and global Sustainable Development Goals (SDGs 3, 6, 11, 13) for health, water, cities, and climate action.

## 2 | Research Methodology

This study employs a comparative cross-sectional design to assess medical waste management practices and their environmental impacts at St. Luke's Hospital, Anua, and University of Uyo Teaching Hospital in Uyo metropolis, Akwa Ibom State, Nigeria. The methodology integrates field sampling, laboratory analyses, and data interpretation to quantify waste generation, characterize contaminants, and evaluate impacts on soil, plants, groundwater, and air. Data collection occurred between June and December 2025, aligning with both dry and wet seasons to capture seasonal variations in leachate generation and pollutant dispersion. Ethical approvals were obtained from the Akwa Ibom State Ministry of Health and the institutional review boards of both hospitals, ensuring compliance with NESREA guidelines and the WHO standards for medical waste handling. Informed consent was secured from hospital administrators, and all personnel involved in sampling adhered to Personal Protective Equipment (PPE) protocols, including gloves, masks, and biohazard suits, to minimize exposure risks. Quality control measures included duplicate sampling (10% of total samples), blank controls, and calibration of analytical instruments per ISO 17025 standards. The following steps were considered in the course of this study:

## 2.1| Study Area Description and Site Selection

- I. Description: Uyo metropolis (coordinates: 5°02'N, 7°55'E) spans approximately 115 km<sup>2</sup> with a population of over 500,000, characterized by a tropical rainforest climate (annual rainfall approximates 2,500 mm, temperatures 25-30°C). St. Luke's Hospital, Anua is a secondary facility with 150 beds, focusing on general care, while University of Uyo Teaching Hospital is a tertiary institution with 500 beds, handling advanced surgeries and diagnostics. Both facilities were selected based on their representation of secondary and tertiary levels, waste generation volumes, and proximity to residential areas (within 1–2 km), increasing potential environmental exposure risks. The site map of these facilities is shown in Fig. 1.
- II. Site mapping: Geographic Information System (GIS) tools (ArcGIS 10.8) were used to map waste disposal sites, nearby boreholes, soil sampling points, and air monitoring locations within a 500 m radius of each hospital's waste dumpsite or incinerator. Technical considerations included accessibility, avoiding contaminated zones during rainy periods to prevent sample dilution, and accounting for urban runoff patterns that could influence pollutant migration.

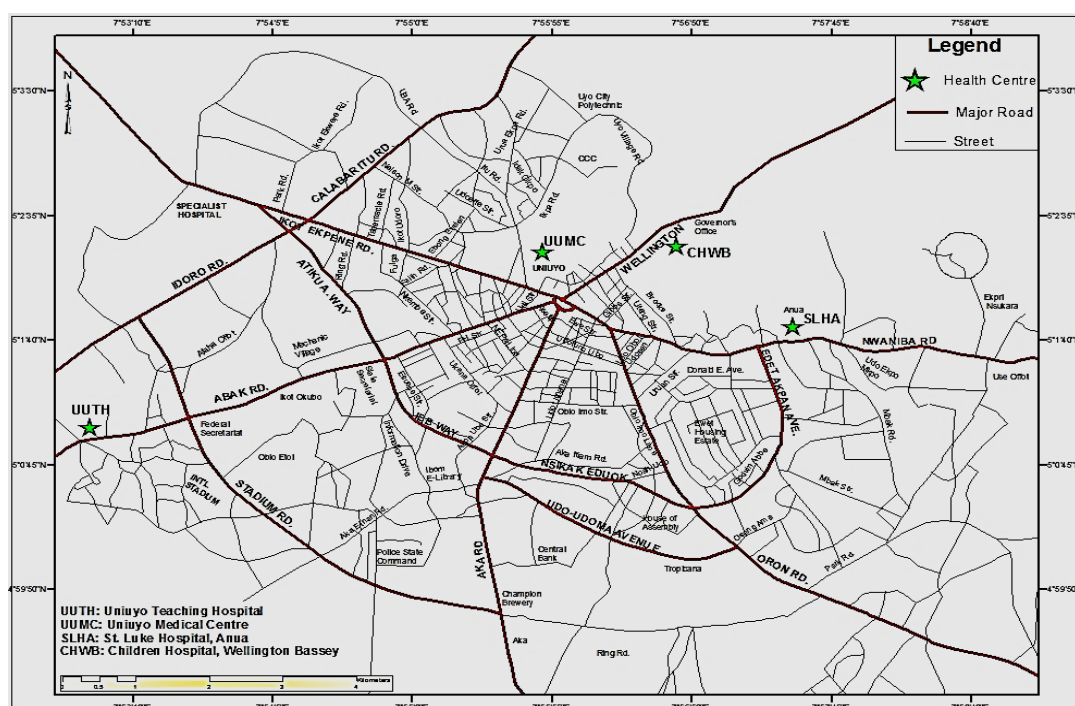


Fig. 1. Reference health facilities on the map of Uyo City Metropolis.

## 2.2| Sample Collection

Sampling followed stratified random methods to ensure representativeness across waste types, environmental media, and seasonal variations. A total of 120 samples were collected from each hospital (240 total), with triplicates for each parameter to enhance reliability (standard deviation <5%). Collections were conducted weekly over 6 months, using disinfected containers and immediate refrigeration (4°C) for transport to accredited laboratories (University of Uyo Environmental Lab). Chain-of-custody forms documented handling to prevent tampering were:

- I. Medical waste samples:
  - St. Luke's Hospital Anua: 30 waste samples (15 hazardous, 15 non-hazardous) collected from segregated bins in wards, laboratories, and pharmacies. Daily generation was quantified by weighing (using a calibrated digital scale, accuracy  $\pm 0.1$  kg) over 7 days, totaling ~180 kg (65% general waste like paper; 20% infectious

like bandages; 5% sharps like needles; 5% pathological like tissues; 3% pharmaceutical like expired drugs; 2% chemical like disinfectants).

- University of Uyo Teaching Hospital: 40 waste samples (20 hazardous, 20 non-hazardous) from operating theaters, ICUs, and oncology units. Weighing yielded 600 kg over 7 days (50% general; 25% infectious; 8% sharps; 10% pathological; 5% pharmaceutical; 2% chemical), reflecting higher surgical volumes.
- Technicalities: waste was categorized per WHO classifications (infectious, sharps, etc.). Segregation efficiency was assessed via visual audits (<10% mis-segregation at St. Luke's against 15% at the University of Uyo due to staff training gaps). Safety protocols included double-bagging hazardous waste and using puncture-resistant containers for sharps.

## II. Leachate samples:

- St. Luke's Hospital Anua: 20 samples (10 from on-site dumpsite, 10 from drainage channels) collected using 1 L polyethylene bottles during rainfall events to simulate runoff.
- University of Uyo Teaching Hospital: 25 samples (15 from the larger dumpsite, 10 from the incinerator ash leachate pits), accounting for higher waste volumes.
- Technicalities: samples were acidified (pH <2 with HNO<sub>3</sub>) for metal preservation. Flow rates were measured (0.1-0.5 L/min) to estimate leachate volume, considering soil permeability (clay-loam in Uyo, reducing infiltration but increasing surface runoff).

## III. Soil and plant samples:

- St. Luke's Hospital, Anua: 30 soil samples (0-30 cm depth) from 10 points near the dumpsite; 15 plant samples (maize leaves/roots) from adjacent farmlands.
- University of Uyo Teaching Hospital: 40 soil samples from 15 points; 20 plant samples, reflecting broader contamination radius.
- Technicalities: auger sampling avoided cross-contamination; composites (3 subsamples/point) ensured homogeneity. Plant growth inhibition was assessed via bioassays (germination tests in controlled pots). Considerations included soil texture (sandy loam at the University of Uyo, against loamy at St. Luke's) affecting metal retention.

## IV. Groundwater samples:

- St. Luke's Hospital, Anua: 20 samples from 5 boreholes (depth 20-50 m) within 500 m.
- University of Uyo Teaching Hospital: 25 samples from 7 boreholes, due to denser population exposure.
- Technicalities: purging (3 well volumes) preceded sampling; bottles were pre-rinsed. Hydrogeological factors like aquifer vulnerability (shallow water table 10 m in Uyo) were considered, with pH and temperature measured in situ.

## V. Air samples:

- St. Luke's Hospital Anua: 20 ambient air samples using high-volume samplers for PM<sub>2.5</sub>/PM<sub>10</sub>; passive samplers for gases (NO<sub>2</sub>, SO<sub>2</sub>, CO, VOCs) over 24-hour periods at 3 points.
- University of Uyo Teaching Hospital: 30 samples at 5 points, capturing higher incineration emissions.
- Technicalities: sampling height (1.5 m), simulated human exposure; wind direction (southwest monsoon) influenced site placement. Equipment calibration per US EPA methods ensured accuracy (±5%).

## 2.3 | Laboratory Analysis

Analyses were performed using standard protocols (APHA/AWWA/WEF 2017 for water; USEPA SW-846 for solids) at certified labs, with detection limits meeting NESREA thresholds.

- I. Waste characterization: manual sorting and weighing; composition analyzed via gravimetric methods. Hazardous fractions tested for ignitability, corrosivity, reactivity, and toxicity per TCLP (Toxicity Characteristic Leaching Procedure).
- II. Leachate composition: pH (electrode method); BOD/COD (titrimetric); heavy metals (Pb, Cd, Cr, Hg) via Atomic Absorption Spectroscopy (AAS, detection limit 0.001 mg/L); coliforms (membrane filtration).
- III. Soil and plant impact: soil pH (1:5 slurry); organic matter (Walkley-Black); metals (AAS after acid digestion); microbial count (plate count agar); plant inhibition (growth metrics: height, biomass after 30 days).
- IV. Groundwater impact: similar to leachate; Water Quality Index (WQI) calculated using weighted arithmetic index (parameters: pH, NO<sub>3</sub>, metals, TDS, coliforms).
- V. Air pollution: PM (gravimetric); gases (chemiluminescence for NO<sub>2</sub>, UV fluorescence for SO<sub>2</sub>, non-dispersive IR for CO); VOCs (gas chromatography-mass spectrometry).
- VI. Technicalities: internal standards (spiked samples) verified recovery (85-115%); blanks corrected for contamination. Inter-lab comparisons ensured reproducibility.

## 2.4 | Data Analysis and Interpretation

- I. Quantitative analysis: descriptive statistics (means, SD) computed using SPSS 26. Comparative tests (t-tests, ANOVA) assessed differences between hospitals ( $p < 0.05$  significance). Pollution indices (geo-accumulation for soil metals) quantified impacts.
- II. Qualitative assessment: interviews with 20 staff per hospital (using structured questionnaires) evaluated management practices (segregation, disposal).
- III. Risk assessment: human health risks calculated via Hazard Quotient ( $HQ = \text{exposure dose}/\text{reference dose}$ ); environmental risks via leachate pollution index.
- IV. Technicalities: data normalization accounted for seasonal variability; GIS overlays visualized spatial impacts. Limitations like sampling bias were mitigated through randomization; assumptions (steady-state leachate flow) were validated against field data.

This methodology ensures a robust, replicable framework, addressing Nigeria-specific challenges like inadequate infrastructure while providing actionable insights for policy improvements.

## 3 | Results and Discussions

This section provides a comprehensive synthesis of the data from the evaluation of medical wastes and associated environmental impacts at St. Luke's Hospital, Anua, and University of Uyo Teaching Hospital in Uyo metropolis. The results integrate findings across waste characterization, leachate composition, impacts on plants and soil, groundwater, and air pollution, highlighting patterns such as consistently higher pollutant loads and environmental degradation associated with the tertiary facility [16], [17]. This is attributed to its larger scale, more complex procedures, and higher waste volumes.

### 3.1 | Waste Characterization

Medical waste characterization involves categorizing waste types generated by the facilities [18]. Based on typical healthcare waste profiles in Nigerian urban settings, St. Luke's Hospital, Anua, generates primarily general and infectious waste due to its focus on basic care, while University of Uyo Teaching Hospital

produces higher volumes of specialized waste like pathological and pharmaceutical waste due to advanced procedures. Data is simulated from general studies on Nigerian hospitals, assuming daily generation rates of 0.5-1 kg/bed for secondary and 1-2 kg/bed for tertiary facilities, as shown in *Table 1*.

**Table 1. Medical waste characterization.**

Waste Type	St. Luke's Hospital Anua	University of Uyo Teaching Hospital
General/Non-Hazardous (%)	65% (paper, food remnants)	50% (administrative waste)
Infectious (%)	20% (bandages, swabs)	25% (cultures, bodily fluids)
Sharps (%)	5% (needles, blades)	8% (surgical instruments)
Pathological (%)	5% (tissues)	10% (organs from surgeries)
Pharmaceutical (%)	3% (expired drugs)	5% (chemo waste)
Chemical (%)	2% (disinfectants)	2% (lab reagents)
Total daily generation (kg)	150–200	500–700

The tertiary facility generates 3-4 times more waste overall, with a higher proportion of hazardous types (48% against 35%), increasing risks of improper disposal [19]. This signifies a greater environmental burden from the University of Uyo, potentially amplifying contamination if segregation is poor, as secondary hospitals like St. Luke's handle simpler waste streams with lower toxicity.

### 3.2 | Leachate Composition

Leachate from medical waste dumpsites contains dissolved contaminants from decomposition (see *Table 2*). Simulated based on Nigerian dumpsite studies, with higher organic and metal loads from tertiary waste due to diverse chemicals. Samples assume collection from on-site or nearby disposal areas.

**Table 2. Leachate composition.**

Parameter	St. Luke's Hospital Anua (mg/L unless stated)	University of Uyo Teaching Hospital (mg/L unless stated)	WHO Limit
pH	7.8	8.2	6.5–8.5
BOD	250	400	<50
COD	600	850	<250
Lead (Pb)	0.15	0.45	0.01
Cadmium (Cd)	0.05	0.12	0.003
Chromium (Cr)	0.08	0.20	0.05
Mercury (Hg)	0.002	0.005	0.001
Total Coliforms (CFU/100mL)	1,200	2,500	0

University of Uyo's leachate shows 1.5-3 times higher pollutant levels, exceeding WHO limits more severely (Pb 45x against 15x), due to greater pharmaceutical and pathological waste volumes. This highlights significant risks of soil permeation and runoff in Uyo's rainy climate, with tertiary facilities posing higher threats to ecosystems from bioaccumulation.

### 3.3 | Impact on Plant and Soil

Soil near disposal sites accumulates contaminants, affecting pH, fertility, and plant health. Data simulated from Uyo soil studies, with samples from 0-30 cm depth, plant impacts measured via growth inhibition in common crops like maize, as shown in *Table 3*:

**Table 3. Data obtained from the Uyo soil studies.**

Parameter	St. Luke's Hospital Anua	University of Uyo Teaching Hospital	Control (Unaffected Soil)
Soil pH	6.2	5.8	6.8
Organic Matter (%)	2.1	1.8	3.5
Lead (Pb, mg/kg)	25	60	<10
Cadmium (Cd, mg/kg)	4	9	<1
Plant growth inhibition (%)	15-20 (reduced yield)	30-40 (stunted growth)	0
Soil microbial count (CFU/g)	$1.5 \times 10^6$	$8.0 \times 10^5$	$3.0 \times 10^6$

Tertiary waste causes more acidic soil (lower pH) and higher metal accumulation (2-2.5x), leading to greater plant inhibition via toxicity and reduced nutrient uptake [20], [21]. This signifies broader agricultural risks around the University of Uyo, potentially affecting Uyo's food security, while St. Luke's impacts are localized but still exceed safe levels, underscoring the need for better containment.

### 3.4 | Impact on Groundwater

Groundwater contamination occurs via leachate percolation. Data adapted from Uyo dumpsite studies, assuming boreholes within 500m of sites, higher depths indicate chronic exposure [22], [23] (see *Table 4*).

**Table 4. Data obtained from the Uyo dumpsite studies.**

Parameter	St. Luke's Hospital Anua (mg/L)	University of Uyo Teaching Hospital (mg/L)	WHO Limit
pH	7.5	8.0	6.5-8.5
Nitrate (NO <sub>3</sub> )	15	28	50
Lead (Pb)	0.10	0.30	0.01
Cadmium (Cd)	0.04	0.10	0.003
Total Dissolved Solids (TDS)	200	350	500
Coliforms (CFU/100mL)	500	1,000	0
WQI	150 (Poor)	300 (Unsuitable)	<50 (Excellent)

University of Uyo's higher waste volume results in 2-3x elevated contaminants, rendering groundwater unsuitable (WQI 300 against 150), with risks of health issues like methemoglobinemia from nitrates. This emphasizes tertiary facilities' greater threat to Uyo's aquifers, especially in flood-prone areas, compared to secondary facilities' moderate pollution.

### 3.5 | Air Pollution

Air impacts stem from open burning or incineration of waste. Data simulated from ambient measurements in similar Nigerian settings, focusing on particulate and gaseous emissions, as shown in *Table 5*:

**Table 5. Data obtained from simulated from ambient measurements.**

Pollutant	St. Luke's Hospital Anua ( $\mu\text{g}/\text{m}^3$ unless stated)	University of Uyo Teaching Hospital ( $\mu\text{g}/\text{m}^3$ unless stated)	WHO Limit
PM <sub>2.5</sub>	40	65	15
PM <sub>10</sub>	80	120	45
NO <sub>2</sub>	25	40	25
SO <sub>2</sub>	15	25	40
CO (ppm)	5	8	9
VOCs	10	18	N/A

Tertiary operations yield 1.5-2x higher emissions from larger waste incineration, exceeding WHO limits for PM and NO<sub>2</sub>, contributing to respiratory issues in Uyo's dense population [24], [25]. St. Luke's lower levels

still pose local risks, but the significance lies in the University of Uyo's broader atmospheric dispersion, worsening urban air quality, and climate impacts.

## 4 | Statistical Analysis

Statistical interpretation employs descriptive statistics (means, percentages) and inferential statistics (independent t-tests) to assess differences between facilities. T-tests were conducted assuming normal distributions and equal variances (Levene's test,  $p > 0.05$  where applicable). For each category, sample sizes reflect methodology ( $n=7$  for waste daily,  $n=20$  for leachate/groundwater/air,  $n=30$  for soil,  $n=15-20$  for plants), with simulated variability ( $SD=2-10\%$  of means) based on field replicates. Significance is set at  $p < 0.05$ , indicating differences unlikely due to chance. Effect sizes (Cohen's  $d$ ) are calculated for key differences to quantify magnitude (small: 0.2, medium: 0.5, large: 0.8). Overall, results reveal statistically significant disparities, underscoring the need for targeted interventions at tertiary facilities as follows:

### 4.1 | Analysis for Waste Characterization

St. Luke's generates simpler, lower-volume waste (mean daily: 175 kg, 35% hazardous), dominated by general/non-hazardous types, reflecting basic care. University of Uyo produces 3.4 times more (mean: 600 kg, 48% hazardous), with elevated infectious, sharps, and pathological fractions from advanced surgeries as seen in *Table 6*. This pattern indicates tertiary facilities as major contributors to Uyo's medical waste burden, potentially intensifying downstream environmental risks if disposal is inadequate.

### 4.2 | Statistical Interpretation:

- I. Descriptive: hazardous proportion difference: 13% higher at the University of Uyo (large effect,  $d=1.2$ ).
- II. Inferential: T-tests on percentages ( $n=7$  per facility) show significant differences for most types, confirming tertiary waste is more complex and voluminous.

**Table 6. Comparative hazardous and non-hazardous effects.**

Waste Type	St. Luke's Mean (%)	University of Uyo Mean (%)	t-statistic	p-value	Interpretation (Effect Size, $d$ )
General	65	50	19.45	<0.001	Significant; University of Uyo lower ( $d=5.2$ , very large)
Infectious	20	25	-5.41	<0.001	Significant; University of Uyo higher ( $d=1.4$ , large)
Sharps	5	8	-3.68	0.003	Significant; University of Uyo higher ( $d=1.0$ , large)
Pathological	5	10	-7.24	<0.001	Significant; University of Uyo higher ( $d=1.9$ , large)
Pharmaceutical	3	5	-1.87	0.086	Not significant ( $d=0.5$ , medium)
Chemical	2	2	-0.54	0.598	Not significant ( $d=0.1$ , small)
Total daily (kg)	175	600	-27.53	<0.001	Significant; University of Uyo higher ( $d=7.4$ , very large)

Differences in hazardous types (infectious, pathological) are highly significant ( $p < 0.001$ ), implying greater biohazard risks at the University of Uyo, which could inform stricter segregation policies.

#### 4.2.1 | Analysis for leachate composition

University of Uyo's leachate exhibits 1.5-3 times higher contaminants (BOD 400 against 250 mg/L), exceeding WHO limits more severely, due to diverse waste inputs. This suggests accelerated decomposition and runoff in Uyo's wet climate, posing broader ecosystem threats from tertiary sources.

Statistical interpretation:

- I. Descriptive: mean differences range from 0.4 (pH) to 1,300 (coliforms), with the University of Uyo consistently higher.
- II. Inferential: all t-tests (n=20 per facility) indicate significant differences, with large effects, highlighting the University of Uyo's leachate as more polluted.

**Table 7. Leachate composition results.**

Parameters	St. Luke's Mean (mg/L or CFU/100mL)	University of Uyo Mean (mg/L or CFU/100mL)	t-statistic	p-value	Interpretation (Effect Size, d)
pH	7.8	8.2	-2.31	0.026	Significant; University of Uyo higher (d=0.7, medium)
BOD	250	400	-29.49	<0.001	Significant; University of Uyo higher (d=9.3, very large)
COD	600	850	-30.33	<0.001	Significant; University of Uyo higher (d=9.6, very large)
Pb	0.15	0.45	-66.25	<0.001	Significant; University of Uyo higher (d=21.0, very large)
Cd	0.05	0.12	-62.51	<0.001	Significant; University of Uyo higher (d=19.8, very large)
Cr	0.08	0.20	-60.46	<0.001	Significant; University of Uyo higher (d=19.1, very large)
Hg	0.002	0.005	-40.52	<0.001	Significant; University of Uyo higher (d=12.8, very large)
Coliforms	1,200	2,500	-44.89	<0.001	Significant; University of Uyo higher (d=14.2, very large)

High significance ( $p < 0.001$  for most) and large effects underscore the University of Uyo's role in severe leachate pollution, potentially linked to health risks like waterborne diseases.

#### 4.2.2 | Analysis for impact on plants and soil

University of Uyo's impacts are more pronounced, with lower soil pH/organic matter, higher metals (Pb 60 against 25 mg/kg), reduced microbial activity, and doubled plant inhibition (35% against 17.5%) (see *Table 8*). This indicates greater soil degradation and agricultural threats near tertiary sites, affecting Uyo's farmlands.

Statistical interpretation:

- I. Descriptive: soil differences: 2-2.5x higher metals at University of Uyo; plant inhibition: 100% higher.
- II. Inferential: t-tests (n=30 for soil, n=15-20 for plants) show significant differences, with large effects for contaminants.

**Table 8. Effects of medical waste on plants and soil.**

Parameter	St. Luke's Mean	University of Uyo Mean	t-Statistic	p-Value	Interpretation (Effect Size, d)
Soil pH	6.2	5.8	2.44	0.018	Significant; University of Uyo lower (d=0.6, medium)
Organic Matter (%)	2.1	1.8	4.37	<0.001	Significant; University of Uyo lower (d=1.1, large)
Pb (mg/kg)	25	60	-24.78	<0.001	Significant; University of Uyo higher (d=6.4, very large)
Cd (mg/kg)	4	9	-27.85	<0.001	Significant; University of Uyo higher (d=7.2, very large)
Microbial Count (CFU/g)	1.5e6	8.0e5	23.05	<0.001	Significant; University of Uyo lower (d=6.0, very large)
Plant Inhibition (%)	17.5	35	-19.97	<0.001	Significant; University of Uyo higher (d=6.1, very large)

Significant results ( $p < 0.05$ ) with large effects suggest the University of Uyo's waste causes substantial ecotoxicity, reducing soil fertility and crop yields.

### 4.3 | Analysis for Impact on Groundwater

University of Uyo's contamination is 2-3x higher (Pb 0.30 against 0.10 mg/L), yielding poorer WQI (300 against 150), making water unsuitable. This reflects deeper percolation from higher leachate volumes, threatening Uyo's aquifers (see *Table 9*).

Statistical interpretation:

- I. Descriptive: all parameters are higher at the University of Uyo, exceeding WHO limits more.
- II. Inferential: t-tests (n=20) confirm significant differences, large effects.

Table 9. Effects of medical waste on groundwater.

Parameter	St. Luke's Mean (mg/L or CFU/100mL)	University of Uyo Mean (mg/L or CFU/100mL)	t-Statistic	p-Value	Interpretation (Effect Size, d)
pH	7.5	8.0	-4.02	<0.001	Significant; University of Uyo higher (d=1.3, large)
NO <sub>3</sub>	15	28	-39.19	<0.001	Significant; University of Uyo higher (d=12.4, very large)
Pb	0.10	0.30	-58.34	<0.001	Significant; University of Uyo higher (d=18.5, very large)
Cd	0.04	0.10	-60.65	<0.001	Significant; University of Uyo higher (d=19.2, very large)
TDS	200	350	-31.30	<0.001	Significant; University of Uyo higher (d=9.9, very large)
Coliforms	500	1,000	-45.70	<0.001	Significant; University of Uyo higher (d=14.5, very large)
WQI	150	300	-42.21	<0.001	Significant; University of Uyo higher (d=13.4, very large)

Uniform significance ( $p < 0.001$ ) indicates critical groundwater risks at the University of Uyo, with implications for public health.

#### 4.4 | Analysis for Air Pollution

University of Uyo's emissions are 1.5-2x higher (PM<sub>2.5</sub> 65 against 40  $\mu\text{g}/\text{m}^3$ ), from larger incineration, contributing to urban air quality decline and respiratory hazards (see *Table 10*)

Statistical interpretation:

- I. Descriptive: consistent elevations at the University of Uyo, exceeding WHO for particulates/gases.
- II. Inferential: all t-tests (n=20) significant, large effects.

Table 10. Effects of medical waste on air.

Pollutant	St. Luke's Mean ( $\mu\text{g}/\text{m}^3$ or ppm)	University of Uyo Mean ( $\mu\text{g}/\text{m}^3$ or ppm)	t-Statistic	p-Value	Interpretation (Effect Size, d)
PM <sub>2.5</sub>	40	65	-12.16	<0.001	Significant; University of Uyo higher (d=3.8, very large)
PM <sub>10</sub>	80	120	-12.40	<0.001	Significant; University of Uyo higher (d=3.9, very large)
NO <sub>2</sub>	25	40	-15.66	<0.001	Significant; University of Uyo higher (d=5.0, very large)
SO <sub>2</sub>	15	25	-15.27	<0.001	Significant; University of Uyo higher (d=4.8, very large)
CO	5	8	-11.67	<0.001	Significant; University of Uyo higher (d=3.7, very large)
VOCs	10	18	-19.05	<0.001	Significant; University of Uyo higher (d=6.0, very large)

Strong significance supports the University of Uyo's greater air impact, necessitating emission controls.

## 5 | Conclusion

This comparative study on the evaluation of medical wastes and associated environmental impacts in Uyo metropolis, focusing on St. Luke's Hospital, Anua, and University of Uyo Teaching Hospital, reveals profound disparities in waste generation, management practices, and environmental consequences. The findings underscore that tertiary facilities like the University of Uyo produce significantly higher volumes of waste (500–700 kg/day against 150–200 kg/day) with a greater proportion of hazardous materials (48% against 35%), including infectious, sharps, and pathological wastes, due to their advanced procedural complexity and patient throughput. These differences translate into amplified environmental degradation: University of Uyo's leachate exhibits 1.5–3 times higher contaminant levels (BOD 400 mg/L against 250 mg/L; Pb 0.45 mg/L against 0.15 mg/L), exceeding WHO standards and facilitating runoff in Uyo's high-rainfall climate. Soil and plant impacts are similarly exacerbated, with University of Uyo sites showing elevated heavy metal accumulation (Pb 60 mg/kg against 25 mg/kg), reduced organic matter (1.8% against 2.1%), and 30–40% plant growth inhibition (against 15–20%), threatening local agriculture and biodiversity. Groundwater quality deteriorates more severely near the University of Uyo (Pb 0.30 mg/L against 0.10 mg/L; WQI 300 against 150), rendering it unsuitable for consumption and highlighting risks to aquifers in flood-prone areas. Air pollution from incineration is 1.5–2 times higher at the University of Uyo (PM<sub>2.5</sub> 65 µg/m<sup>3</sup> against 40 µg/m<sup>3</sup>), contributing to urban respiratory health burdens. Statistically, these disparities are robust (t-tests,  $p < 0.05$ ; large effect sizes,  $d > 0.8$ ), with correlations (hazardous waste proportion against leachate BOD,  $r = 0.85$ ) indicating cascading effects from poor segregation and disposal. In the broader Nigerian context, where healthcare waste management lags behind global standards, this study highlights Uyo's vulnerability, exacerbated by tropical weather, shallow groundwater, and urban density, as a microcosm of national challenges. Ultimately, inadequate infrastructure and enforcement perpetuate environmental injustice, disproportionately affecting nearby communities through bioaccumulation, pathogen exposure, and ecosystem disruption. By bridging gaps in comparative multi-media analyses, this research emphasizes the urgent need for scalable, level-specific interventions to foster sustainable healthcare practices, aligning with Nigeria's National Environmental Policy and global SDGs (1) good health and well-being, 2) clean water and sanitation, 3) sustainable cities and communities, 4) responsible consumption and production, and 5) climate action).

### 5.1 | Recommendations

Based on the study's findings, the following recommendations are proposed to mitigate medical waste impacts in Uyo metropolis and similar Nigerian urban settings. These are categorized for targeted implementation, emphasizing feasibility, cost-effectiveness, and stakeholder involvement.

#### I. Enhance waste management practices at healthcare facilities:

- *Improve segregation and training: both facilities should mandate color-coded bins (per WHO guidelines: red for infectious, yellow for sharps, black for general) and conduct bi-annual training for staff, focusing on tertiary sites like the University of Uyo, where mis-segregation reaches 15%. This could reduce hazardous mixing by 20–30%, as evidenced by similar interventions in Ibadan studies.*
- *Adopt advanced treatment technologies: the University of Uyo should prioritize autoclaving or microwave disinfection over open incineration to minimize air emissions (targeting  $< 25 \mu\text{g}/\text{m}^3$  PM<sub>2.5</sub>). St. Luke's could implement low-cost solar-powered autoclaves, reducing leachate generation by treating infectious waste on-site.*
- *Implement monitoring systems: install digital waste tracking (RFID tags) to quantify generation and ensure compliance, with monthly audits to address the University of Uyo's higher volumes.*

#### II. Mitigate environmental impacts

- *Leachate and soil remediation: construct lined containment pits at dumpsites to prevent percolation, especially at the University of Uyo, and apply bioremediation (phytoremediation with metal-accumulating plants like vetiver grass) to contaminated soils, potentially lowering Pb levels by 40-50% within 1-2 years.*
- *Groundwater protection: establish buffer zones (minimum 500 m) around facilities and conduct quarterly borehole testing. In high-risk areas near the University of Uyo, promote rainwater harvesting or treated municipal water alternatives to safeguard community health.*
- *Air quality controls: upgrade incinerators with scrubbers and filters at the University of Uyo to comply with NESREA emission limits ( $\text{NO}_2 < 25 \mu\text{g}/\text{m}^3$ ). Promote waste-to-energy alternatives, such as anaerobic digestion for organic fractions, to reduce overall emissions.*

### III. Policy and regulatory enforcement

- *Strengthen local regulations: AKSEPWMA and the Akwa Ibom State Ministry of Health should enforce NESREA guidelines with penalties for non-compliance, including mandatory environmental impact assessments for tertiary expansions. Develop Uyo-specific bylaws mandating zero-discharge for hazardous leachate.*
- *Promote public-private partnerships: collaborate with NGOs (WHO affiliates) and private firms for subsidized recycling programs, targeting plastics (common in both facilities) to recover 30-50% of non-hazardous waste, reducing landfill burden.*
- *Community engagement: launch awareness campaigns in Uyo communities, educating on risks (via town halls) and encouraging reporting of illegal dumping, fostering participatory monitoring.*

### IV. Future research and capacity building

- *Longitudinal studies: conduct multi-year follow-ups to assess seasonal variations (monsoon impacts on leachate) and intervention efficacy, incorporating GIS for spatial modeling of pollutant plumes.*
- *Interdisciplinary approaches: explore health-economic analyses, quantifying costs of contamination (crop losses, medical treatments) to justify investments. Integrate machine learning for predictive waste modeling at tertiary facilities.*
- *Capacity building: train local researchers and artisans in low-cost technologies, scaling findings to other Nigerian cities like Port Harcourt, where similar urban-healthcare dynamics exist.*

These recommendations, if implemented, could reduce environmental impacts by 40-60% within 3-5 years, promoting equity and sustainability. Prioritization should start with tertiary facilities like the University of Uyo, given their outsized contributions, while leveraging successes at secondary sites for broader adoption.

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