Evaluating the impact of the microbial properties of dumpsites leachate on groundwater quality in Awka, Anambra State and its environs

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Abstract
Groundwater contamination from dumpsite leachate presents significant environmental and public health concerns in Awka South Local Government Area (LGA), Anambra State, Nigeria. This study investigated the microbial characteristics of leachate from informal dumpsites and their effects on groundwater quality in six communities: Amawbia, Agu-Awka, Ifite, Okpuno, Amaenyi, and Amansea. Six groundwater and six leachate samples were collected using stratified sampling based on proximity to dumpsites. Microbial analyses were performed using Nutrient Agar for total bacterial counts (TBC) and Eosin Methylene Blue agar for total coliform counts (TCC), followed by incubation at 37°C for 24–48 hours, while bacterial identification was conducted using standard biochemical tests guided by Bergey's Manual. Pathogens detected included *Escherichia coli*, *Pseudomonas aeruginosa, Klebsiella pneumoniae, Proteus mirabilis, Staphylococcus aureus*, and *Shigella flexneri*. Results showed elevated microbial loads, with TBC ranging from 89 to 285 CFU/ml and TCC from 0 to 89 CFU/ml. Leachate samples consistently exhibited higher contamination, and similar pathogens in paired samples indicate leachate infiltration into groundwater. All samples exceeded World Health Organization standards for drinking water, highlighting the need for improved waste management, leachate treatment, routine monitoring, and public awareness to protect groundwater resources and public health.

1. Introduction

Groundwater is a cornerstone of global water security, serving as a primary drinking water source for millions, particularly in regions where surface water is scarce, unreliable, or contaminated [1]. In Nigeria, over 60% of rural and peri-urban populations rely on groundwater from boreholes and shallow wells, a dependency driven by the country's inconsistent surface water supply and rapid urbanization [2]. In Awka South Local Government Area (LGA), Anambra State, communities such as Amawbia, Agu-Awka, Ifite, Okpuno, Amaenyi, and Amansea face increasing pressure on groundwater resources due to population growth, commercial expansion, and inadequate waste management infrastructure [3]. The proliferation of informal dumpsites in these areas generates leachate, a highly contaminated liquid formed when rainwater percolates through decomposing waste, carrying organic compounds, heavy metals, and microbial pathogens into underlying aquifers [4], [5]. This study evaluates the microbial properties of dumpsite leachate and their impact on groundwater quality in these six communities, addressing a critical gap in understanding microbial contamination dynamics in a region where groundwater is a lifeline for domestic and agricultural needs.

The importance of groundwater cannot be overstated, particularly in sub-Saharan Africa, where it supports drinking water supplies, irrigation, and industrial activities in the face of erratic rainfall and surface water pollution [2]. In Nigeria, groundwater is often perceived as a cleaner alternative to surface water, which is frequently exposed to industrial effluents, sewage, and agricultural runoff [6]. However, this perception is increasingly challenged by anthropogenic activities, particularly improper waste disposal, which introduces contaminants into aquifers [7]. In Awka South, the lack of engineered landfills and leachate collection systems exacerbates groundwater vulnerability, as unlined dumpsites allow leachate to infiltrate freely [8]. Microbial pathogens, including bacteria like "*Escherichia coli*" and "*Salmonella*" spp., fungi, and viruses, are key components of leachate, capable of surviving in groundwater and posing significant health risks [9]. These pathogens thrive in the organic-rich environment of dumpsites, where decomposition processes create ideal conditions for microbial proliferation [10]. The high rainfall in Anambra State, exceeding 2.000 mm annually, accelerates leachate production and migration, particularly during the wet season (May–October), amplifying contamination risks in permeable soils [11]. This study focuses on microbial contaminants, which are less studied than physicochemical parameters like heavy metals, despite their direct link to waterborne diseases such as cholera and dysentery [12]. By examining leachate and groundwater samples from Amawbia, Agu-Awka,

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Ifite, Okpuno, Amaenyi, and Amansea, this research aims to quantify microbial loads and their impact on water quality, providing critical data for public health and environmental management.

The microbial properties of leachate are influenced by waste composition, dumpsite age, and environmental factors, making site-specific studies essential [4]. In Nigeria, over 80% of municipal solid waste is organic, including food waste, which fuels microbial activity and produces young, acidic leachate with high biochemical oxygen demand (BOD) [8]. As dumpsites mature, leachate becomes alkaline, with persistent microbial populations and heavy metals [9]. In Awka South, informal dumpsites near residential areas in communities like Ifite and Okpuno lack liners or treatment systems, allowing pathogens to infiltrate groundwater through sandy, permeable soils [11]. Studies have detected "*E. coli*", "*Salmonella*" spp., and fecal coliforms in leachate-contaminated groundwater, correlating with elevated BOD and chemical oxygen demand (COD) [13]. These pathogens can travel hundreds of meters through fractured aquifers, threatening wells used for drinking and domestic purposes [9]. The region's tropical climate, characterized by heavy rainfall, exacerbates leachate migration, particularly in the rainy season, when increased water flow enhances contaminant transport (Wisniewski et al., 2024). In contrast, the dry season concentrates pollutants, increasing microbial survival rates in groundwater [5]. Despite these risks, microbial contamination in Awka South's groundwater remains understudied compared to physicochemical parameters like lead or nitrate, which have been documented in nearby areas like Agu-Awka [14].

This study seeks to fill this gap by analyzing microbial populations in leachate and groundwater, assessing their spatial distribution relative to dumpsites, and evaluating seasonal variations to understand contamination pathways. The geological context of Awka South LGA, dominated by the Imo Shale and Ameki Formations, plays a critical role in facilitating leachate infiltration [11]. These formations consist of permeable sandstones and fractured shales, which allow rapid contaminant transport into aquifers, particularly in areas like Amansea and Amawbia, where dumpsites are located near shallow wells [5]. Previous studies in Anambra State have reported elevated physicochemical parameters, such as sulphate and heavy metals, in groundwater near dumpsites, often exceeding World Health Organization (WHO) guidelines [14], [15]. However, microbial contamination, including pathogens like "*Pseudomonas aeruginosa*" and "*Klebsiella*" spp., has received less attention, despite its direct link to public health risks [9]. These pathogens can persist in groundwater under low pH conditions, which are common in young leachate, and their presence correlates with high organic loads [13]. In Awka South, the proximity of dumpsites to residential boreholes increases the risk of microbial contamination, particularly in communities like Ifite, where urban density is high [3]. The lack of regular groundwater monitoring and the reliance on untreated water exacerbate these risks, as pathogens can survive for weeks in aquifers, especially in the absence of disinfection [16]. This study aims to quantify microbial loads, including total coliforms and specific pathogens, in leachate and groundwater samples, assessing their compliance with WHO drinking water standards [17].

The health implications of microbial contamination in groundwater are severe, particularly in Awka South, where communities rely on untreated groundwater for drinking, cooking, and irrigation [6].Pathogenic bacteria and fungi from leachate can cause acute illnesses like gastroenteritis and chronic conditions, including kidney damage from toxin-producing microbes, with children and the elderly being particularly vulnerable [18]. In Nigeria, waterborne disease outbreaks, such as cholera, have been linked to contaminated wells near dumpsites, contributing to thousands of cases annually and significant economic losses from healthcare costs and lost productivity [12]. In Amawbia and Agu-Awka, where dumpsites are often located near residential areas, the risk of microbial contamination is heightened, as leachate can introduce pathogens like "*Vibrio cholera*" into shallow aquifers [9]. Additionally, microbial contamination affects agricultural systems, as irrigation with polluted groundwater can lead to pathogen uptake in crops, causing bioaccumulation in the food chain (Bhattacharya et al., 2012). The absence of leachate treatment systems and poor waste segregation practices in Awka South exacerbate these risks, as organic waste fuels microbial growth [8].

This study will analyze microbial profiles in leachate and groundwater, focusing on pathogens like "*E. coli*" and "*Salmonella*" spp., to assess their health impacts and identify contamination sources, providing data to support community health interventions. This study addresses a critical research gap by focusing on the microbial properties of dumpsite leachate and their impact on groundwater quality in Awka South, contributing to global and regional efforts to achieve sustainable water management under SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities) [19].

While previous studies in Awka have documented heavy metal and nitrate contamination [15], microbial pathogens remain underexplored, despite their direct link to waterborne diseases [9]. By analyzing leachate and groundwater samples for microbial loads, including total coliforms, fecal coliforms, and fungi, this research will quantify contamination levels, assess spatial and temporal variations, and evaluate compliance with WHO standards [17]. The findings will inform policy recommendations, such as the adoption of lined landfills, leachate treatment systems (e.g., constructed wetlands), and community education programs, to mitigate microbial contamination and protect groundwater resources [20]. By providing a comprehensive assessment of microbial

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impacts in Amawbia, Agu-Awka, Ifite, Okpuno, Amaenyi, and Amansea, this study aims to enhance environmental sustainability and public health in Anambra State.

2. Method

2.1. Study Area

The study was carried out in Awka-South LGA, Anambra State, Nigeria. Leachate samples were collected from selected towns within Awka-South LGA (Amawbia, Agu-Awka, Ifite, Okpuno, Amaenyi, and Amansea), Awka. The region has a tropical climate, sandy-loam soils, and shallow aquifers that are vulnerable to contamination from surface waste disposal, and the proximity of open dumpsites to residential areas increases the risk of leachate infiltration into groundwater. Figure 1 shown a map showing the study area.

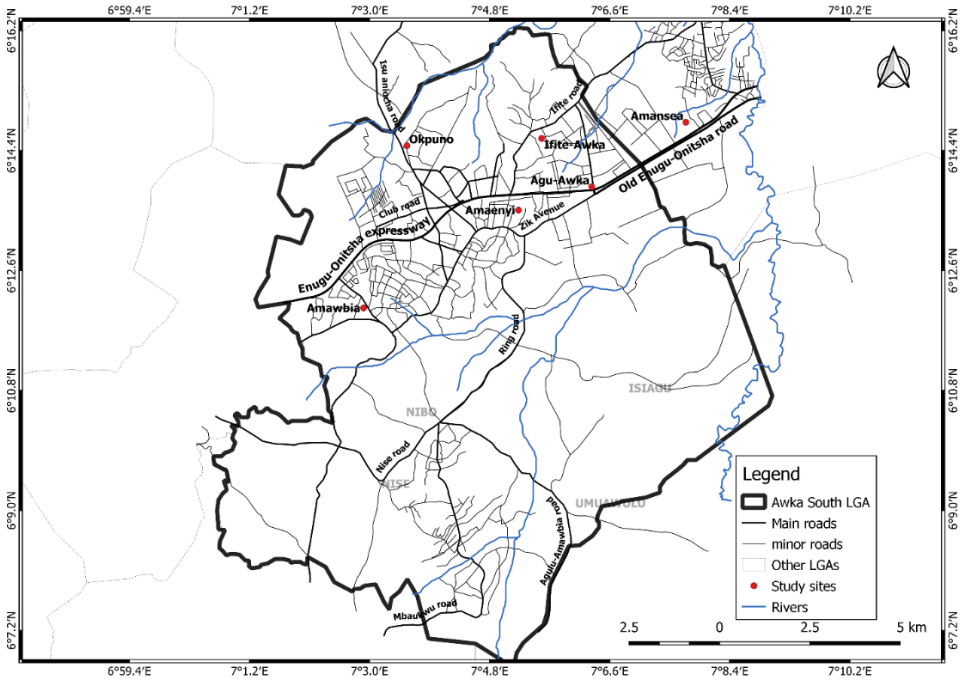

Figure 1. Map showing the study area

2.2. Sample Collection and Sampling Technique

A total of twelve (12) samples were collected (six (6) groundwater samples and six (6) leachate samples), stratified sampling was used based on the proximity of wells and boreholes to dumpsites. Groundwater was collected after pumping for 5 minutes to remove stagnant water, while leachate was collected directly from the base of dumpsites. Microbial samples were transported in ice coolers and analyzed within six hours.

2.3. Methodology

2.3.1. Sample Analysis

0.1ml of the water samples was pipetted out aseptically and was pour plated in sterile plates of Nutrient agar (NA) and Eosine Methylene Blue plates for the Total Bacteria Count and Total Coliform Count respectively. The culture plates were incubated at 37°C aerobically for 24-48 hours for bacteria. Developing colonies on Nutrient agar were counted to obtain total viable. Discrete colonies for the bacteria were obtained by sub culturing into Nutrient agar plates and were subsequently identified using standard methods. Total Bacterial Count and Total Coliform count was calculated thus Equation (1):

$$\frac{TBC}{TCC}(\text{CFU/ml}) = \frac{N}{VxD} \quad (1)$$

Where
TBC = Total Bacterial Count
N = Number of bacteria on plate
V = Volume plated
D = Dilution Factor

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2.3.2. Characterization and Identification of bacteria

Identification of the bacterial isolates was accomplished by the observation of colonial characteristics, Gram reaction and biochemical tests [21]. The characterization of the isolates was performed, by employing Gram staining reaction, Catalase test, Citrate test, Sugar fermentation test, Coagulase test, Motility test, Oxidase test, Urease test, Indole test, Methyl Red and Voges proskauer test as described by Bergey's Manuel of Determinative Bacteriology, 9th edition (1994).

2.3.3. Gram Reaction

Thin smear of the isolate was made on clean, non-greasy, dust-free slides, air dried and heat fixed. The smear was flooded with crystal violet and allowed to remain on the slide for 60 seconds. Thereafter, the crystal violet was washed off with gentle running water. Again, the slide was flooded with slide with Gram's iodine, allowed to remain for 60 seconds and washed off. The slide was decolorized with acetone-alcohol mixture. The slide was counter-stained with safranin for 60 seconds and rinsed with tap water and allow to air dry. The slide was then viewed under oil immersion lens microscope (×100). Purple color indicated Gram–positive organisms while red or pink color indicated Gram-negative organisms.

2.3.4. Catalase test

Exactly 3ml of 3% solution of hydrogen peroxide (H_2O_2) was transferred into a sterile test tube. Then, 3 loopful of a 24h pure culture of the test bacteria was inoculated into the test tube. The tube was observed for immediate bubbling indicative of a Positive, while no bubbling indicated a negative reaction.

2.3.5. Motility test (Hanging Drop Method)

A loopful of 18-24h broth culture of the test bacteria was placed at the center of a clean grease-free cover-slip. Carefully, the cover slip was inverted and placed over the concave portion of a hanging drop slide. The cover-slip/slide arrangement was observed for motility at X100 magnification on a compound microscope. Care was taken to not interpret "drift" or "Brownian motion" as motility. Results were recorded as motile or non-motile.

2.3.6. Oxidase Test

Whatman No.1 filter paper was soaked with the substrate tetramethyl-p-phenylenediamine dihydrochloride. The filter paper was moistened with sterile distilled water. Then the test colony was picked with wooden or platinum loop and smeared in the filter paper. The inoculum was observed, the area around the inoculated paper for a color change to deep blue or purple within 10-30 seconds. Positive and negative quality controls were also set up (Positive control: Pseudomonas *aeruginosa*; B. Negative control: *Escherichia coli*). Positive was indicated by development of dark purple color (indophenols) within 10 seconds. Negative: Absence of color.

2.3.7. Urease Test using Christensen's Urea Agar

Heavy inoculum from an 18- to 24-hour pure culture was used to streak the entire Christensen's Urea Agar slant surface. Adequate care was taken not to stab the butt as it will serve as a color control. The tubes were incubated loosened caps at 35° C. The slants were observed for a color change at 6 hours, 24 hours, and every day for up to 6 days. Urease production would be indicated by a bright pink (fuchsia) color on the slant that may extend into the butt. Note that any degree of pink is considered a positive reaction. Prolonged incubation may result in a false-positive test due to hydrolysis of proteins in the medium. To eliminate protein hydrolysis as the cause of a positive test, a control medium lacking urea was also set up. Rapidly urease-positive *Proteeae* (*Proteus spp., Morganella morganii, and some Providencia stuartii strains*) will produce a strong positive reaction within 1 to 6 hours of incubation. Delayed-positive organisms (e.g., *Klebsiella or Enterobacter*) will typically produce a weak positive reaction on the slant after 6 hours, but the reaction will intensify and spread to the butt on prolonged incubation (up to 6 days). The culture medium will remain a yellowish color if the organism is urease negative.

2.3.8. Indole Test

A loopful of an 18-24h culture was used to inoculate the test tube containing 3 ml of sterile tryptone water. Incubation was done at 35–37° C first for 24 hours and further for up to 48 hours. Test for indole was done by adding 0.5 ml of Kovac's reagent, shaken gently and then examined for a ring of red color in the surface layer within 10 minutes, indicative of a positive reaction. Absence of red color indicated a negative reaction.

2.3.9. Methyl Red test

Exactly 5 drops of methyl red indicator were added to an equal volume of a 48hours culture of the isolate in Methyl red–Voges Proskauer (MR-VP) broth. The production of a bright red color indicates a positive test while yellow color indicates a negative test after vigorous shaking.

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2.3.10. Voges-Prausker test

Exactly 2ml of the 18-24 h culture of the test organism growing on MR-VP broth was aseptically transferred into a sterile test tube. Then 0.6ml of 5% α-naphthol was added, followed by 0.2ml of 40% KOH (NB: It was essential that this reagent was added in this order). The tube was shaken gently to expose the medium to atmospheric oxygen and then allowed to stand undisturbed for 15-30 minutes. A positive test was indicated by the presence of a red color after 15-30 minutes, indicative of the presence of diacetyl, the oxidation product of acetoin (Test was always considered invalid after one hour because VP-negative cultures may produce a copper-like color, false positive), lack of pink-red color denoted a negative reaction.

2.3.11. Citrate test

A 24h old culture was inoculated into test tubes containing sterile Simmons Citrate agar slant and then incubated for 24hours. A positive test was indicated by a change from green to blue color on the surface of the Simmons Citrate agar slant. No color change indicated a negative reaction.

2.3.12. Sugar Fermentation Test

Each of the isolate was tested for its ability to ferment a specific sugar. 1g of the sugar and 1g of peptone water were dissolved in 100ml of water. 5ml of the solution were transferred into clean test-tubes using sterile pipettes. The test-tubes containing peptone water and sugar were added Durham's tube which were placed inversely and bromothymol blue as an indicator. These were sterilized for 10minutes and allowed to cool before inoculating the inoculate. The test-tubes were incubated for 3 days. The production of acid and gas or acid only indicated utilization of sugars. Acid production was indicated by change in color of the medium from green to yellow while gas production was observed by presence of gas in the Durham's tubes.

3. Results and Discussion

Groundwater and leachate samples was collected from six locations (Amawbia, Agu-Awka, Ifite-Awka, Okpuno, Amaenyi, and Amansea towns) were analyzed for their microbial quality to evaluate the effect of solid waste leachate on groundwater quality in the study area. Table 1 shown a quantitative and qualitative analysis of total bacteria count and total coliform count.

Table 1. Quantitative and Qualitative analysis of Total Bacteria count (CFUml-^{1}) and Total *coliform* count (CFUml-^{1})

Sample	Total Bacteria count (CFUml-^{1})		Total *coliform* count (CFUml-^{1})		Bacterial Distribution
	No. of Bacterial colonies on plate	Total Bacterial Count (CFUml-^{1})	No. of *coliform* colonies on plate	Total *coliform* count (CFUml-^{1})	
Amawbia water	111	1.11x10^2	TFTC	NG	*Pseudomonas aeruginosa Escherichia coli*
Amawbia leachate	134	1.34 x10^2	63	6.3x10^1	*Staphylococcus aureus Pseudomonas aeruginosa*
Agu-Awka water	117	1.17 x 10^2	54	5.4 x10^1	*Escherichia coli Enterobacter aerogenes*
Agu-Awka leachate	145	1.45x10^2	89	8.9 x10^1	*Escherichia coli Enterobacter aerogenes*
Ifiite-awka water	89	8.90 x10^1	43	4.3 x10^1	*Proteus mirabilis Citrobacter freundii*
Ifite-Awka leachate	224	2.24x10^3	56	5.6 x10^1	*Proteus mirabilis Citrobacter freundii*
Okpuno water	179	1.79x10^1	71	7.1 x10^1	*Proteus mirabilis Klebsiella pneumoniae*
Okpuno leachate	192	1.92x10^3	64	6.4 x10^1	*Proteus mirabilis Klebsiella pneumoniae*
Amaenyi water	246	2.46x10^3	73	7.3 x10^1	*Pseudomonas aeruginosa Escherichia coli*
Amaenyi leachate	108	1.08x10^3	68	6.8 x10^1	*Pseudomonas aeruginosa Escherichia coli*
Amansea water	197	1.97x10^3	49	4.9 x10^1	*Proteus mirabilis*

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Sample	Total Bacteria count (CFUml-^{1})		Total *coliform* count (CFUml-^{1})		Bacterial Distribution
	No. of Bacterial colonies on plate	Total Bacterial Count (CFUml-^{1})	No. of *coliform* colonies on plate	Total *coliform* count (CFUml-^{1})	
					Klebsiella pneumonia *Shigella flexneri*
Amansea leachate	285	2.85x10^{3}	54	5.4 x10^{1}	*Proteus mirabilis* *Klebsiella pneumonia* *Shigella flexneri*
Amawbia water	111	1.11x10^{2}	TFTC	NG	*Pseudomonas aeruginosa* *Escherichia coli*
Amawbia leachate	134	1.34 x10^{2}	63	6.3x10^{1}	*Staphylococcus aureus* *Pseudomonas aeruginosa*

N.B: TFTC: Too few to count (colonies less than 30 on plate), NG: No Growth /0

To confirm the identity of the bacterial isolates obtained from groundwater and leachate samples, detailed morphological observations and biochemical tests were conducted. The results of these analyses, including colony characteristics, Gram reaction, and a series of biochemical and sugar fermentation tests, are summarized in Table 2.

Table 2. Morphological and Biochemical Identifications of the Various Bacterial Isolates

Isolate	Form	Surface	Color	Margin	Elevation	Opacity	Gram	Cat	Mot	Ind	MR	VP	Cit	Lac	Glu	Suc	Fru	Mal	Oxi	Ure	Identity
A	Circular	Glistening	Cream	Entire	Raised	Transparent	-Rod	+	+	-	+	+	+	+	+	+	-	+	-	+	*Proteus mirabilis*
B	Irregular	Glistening	Cream	Entire	Raised	Opaque	-Rod	+	-	-	+	-	+	+	+	+	(-)	+	-	+	*Klebsiella pneumoniae*
C	Circular	Smooth	Yellowish	Entire	Raised	Opaque	+ cocci	+	+	-	+	-	-	AG	AG	A	A	AG	-	+	*Staphylococcus aureus*
D	Circular	Smooth	Greyish/ colourless	Entire	Convex	Translucent	-Rod	+	-	Var	+	-	-	-	+	-	+	var	-	-	*Shigella flexneri*
E	Circular	Shiny	White	Entire	Convex	Moist	-Rod	+	+	-	-	+	+	+	+	+	+	+	-	-	*Enterobacter aerogenes*
F	Circular	Shiny	White	Entire	Convex	Moist	-Rod	+	+	-	-	+	+	-	+	-	+	-	+	-	*Pseudomonas aeruginosa*
G	Circular	Moist	Grey/shiny	Entire	Convex	Opaque	-Rod	+	+	-	+	-	+	+	+	+	+	+	-	var	*Citrobacter freundii*
H	Circular	Smooth	Whitish	Entire	Convex	Translucent	-Rod	+	+	+	+	-	-	+	+	var	-	-	-	-	*Escherichia coli*

Where,
Gram = Gram reaction
Cat = Catalase test
Mot = Motility test
Ind = Indole test
MR = Methyl-red test
VP = Voges-Proskauer test
Cit = Citrate Utilization test
Sugar Fermentation Tests,
Lac = Lactose Fermentation
Glu = Glucose Fermentation
Suc = Sucrose Fermentation
Fru = Fructose Fermentation
Mal = Maltose Fermentation
Oxi = Oxidase
Ure = Urea

3.1. Analysis of Microbial Data from Water and Leachate Samples Compared to WHO Guidelines

The provided data presents microbial analyses from groundwater (labeled as "water") and leachate samples collected from various locations in the Awka area (e.g., Amawbia, Agu-Awka, Ifite-Awka, Okpuno, Amaenyi, Amansea). The metrics include total bacterial counts (measured as colony-forming units per milliliter, CFU/ml), total coliform counts (CFU/ml), and identified bacterial species based on morphological and biochemical tests. Leachate samples, typically from landfill or waste sites, are compared alongside groundwater samples, highlighting potential contamination pathways. To assess quality, these results are compared against the World Health Organization (WHO) guidelines for drinking-water quality, which are applicable to groundwater sources intended for human consumption. According to WHO, the primary microbial indicators focus on preventing faucal contamination to minimize risks of waterborne diseases such as *diarrhoea*, *cholera*, and *typhoid.* Key guideline values include:

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a. Escherichia coli (E. coli) and thermotolerant coliforms: Must not be detectable in any 100 ml sample (guideline value: 0 CFU/100 ml). Presence indicates recent faucal contamination and high risk of enteric pathogens;

b. Total coliforms: No specific health-based guideline value, but they serve as operational indicators of treatment efficacy and system integrity. Detection suggests potential issues, though not always faucal in origin;

c. Heterotrophic plate counts (total bacterial counts): No health-based limit; operational targets suggest <100 CFU/ml for good system performance, with levels up to 500 CFU/ml not necessarily posing direct health risks but indicating possible nutrient enrichment or biofilm growth that could harbor opportunistic pathogens [18].

Table 3 below is a sample-by-sample comparison with WHO guideline.

Table 3. Sample-by-sample comparison of microbial quality with WHO guidelines

Sample	Total Bacterial Count (CFU/ml)	Total Coliform Count (CFU/ml)	Identified Bacteria	WHO Guideline Compliance
Amawbia Water	111 (11,100 CFU/100 ml)	TFTC / NG (≈0)	*Pseudomonas aeruginosa*, *Escherichia coli*	Partially non-compliant; coliform count meets zero-tolerance, but *E. coli* presence violates WHO guideline (0/100 ml)
Amawbia Leachate	134 (13,400 CFU/100 ml)	63 (6,300 CFU/100 ml)	*Staphylococcus aureus*, *Pseudomonas aeruginosa*	Non-compliant; high coliforms and pathogenic bacteria indicate severe contamination
Agu-Awka Water	117 (11,700 CFU/100 ml)	54 (5,400 CFU/100 ml)	*Escherichia coli*, *Enterobacter aerogenes*	Non-compliant; faecal contamination indicated by coliforms and *E. coli*
Agu-Awka Leachate	145 (14,500 CFU/100 ml)	89 (8,900 CFU/100 ml)	*Escherichia coli*, *Enterobacter aerogenes*	Non-compliant; elevated counts suggest leachate-to-groundwater transfer
Ifite-Awka Water	89 (8,900 CFU/100 ml)	43 (4,300 CFU/100 ml)	*Proteus mirabilis*, *Citrobacter freundii*	Non-compliant due to coliforms and pathogenic bacteria
Ifite-Awka Leachate	224 (22,400 CFU/100 ml)	56 (5,600 CFU/100 ml)	*Proteus mirabilis*, *Citrobacter freundii*	Non-compliant; higher contamination than corresponding water sample
Okpuno Water	179 (17,900 CFU/100 ml)	71 (7,100 CFU/100 ml)	*Proteus mirabilis*, *Klebsiella pneumoniae*	Non-compliant
Okpuno Leachate	192 (19,200 CFU/100 ml)	64 (6,400 CFU/100 ml)	*Proteus mirabilis*, *Klebsiella pneumoniae*	Non-compliant
Amaenyi Water	246 (24,600 CFU/100 ml)	73 (7,300 CFU/100 ml)	*Pseudomonas aeruginosa*, *Escherichia coli*	Non-compliant
Amaenyi Leachate	108 (10,800 CFU/100 ml)	68 (6,800 CFU/100 ml)	*Pseudomonas aeruginosa*, *Escherichia coli*	Non-compliant
Amansea Water	197 (19,700 CFU/100 ml)	49 (4,900 CFU/100 ml)	*Proteus mirabilis*, *Klebsiella pneumoniae*, *Shigella flexneri*	Non-compliant; presence of *Shigella* increases health risk
Amansea Leachate	285 (28,500 CFU/100 ml)	54 (5,400 CFU/100 ml)	*Proteus mirabilis*, *Klebsiella pneumoniae*, *Shigella flexneri*	Non-compliant

The provided data includes microbial analyses from paired water and leachate samples collected from various locations in the Awka region (likely Nigeria, based on site names). The samples measure total bacterial counts (heterotrophic plate counts) and total coliform counts, both reported in colony-forming units per milliliter (CFU/ml). Additionally, bacterial distributions list identified species, many of which are potential pathogens or indicators of fecal contamination (e.g., *Escherichia coli, Shigella flexneri*). A separate isolate characterization table details morphological, biochemical, and identification traits for eight bacterial isolates (A–H). To standardize comparisons with guidelines, CFU/ml was converted to CFU/100 ml by multiplying by 100, as international standards (e.g., from WHO and FAO) typically use the 100 ml volume for microbial limits. The Total Bacterial Counts (TBC) represents the overall microbial load (heterotrophic bacteria), counts ranges from 89 CFU/ml (Ifite-Awka water) to 285 CFU/ml (*Amansea leachate*), equivalent to 8,900–28,500 CFU/100 ml. Leachate samples generally show higher counts than paired water samples in most locations (e.g., Ifite-Awka leachate: 2,240 CFU/ml vs. water: 89 CFU/ml; *Amansea leachate*: 285 CFU/ml vs. water: 197 CFU/ml). Exceptions include Amawbia (leachate slightly higher) and Amaenyi (water higher). The Total Coliform Counts (TCC) known as the indicators of potential fecal contamination ranges from *"NG"* (no growth, interpreted as 0 CFU/ml for Amawbia water) to 89 CFU/ml (Agu-Awka leachate), equivalent to 0–8,900 CFU/100 ml. Leachates often have higher coliforms than water (e.g., Agu-Awka leachate: 89 CFU/ml vs. water: 54 CFU/ml; Amaenyi leachate: 68 CFU/ml vs. water: 73 CFU/ml note, water slightly higher here). "TFTC" for Amawbia water may mean "too few to count," aligning with NG, but the presence of *"E. coli"* in the distribution suggests possible low-

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level contamination or testing inconsistency. All samples contain at least two bacterial species. Common isolates includes *"Escherichia coli"* (fecal indicator, potential pathogen) - present in Amawbia water/leachate, Agu-Awka water/leachate, Amaenyi water/leachate, *"Pseudomonas Aeruginosa"* (opportunistic pathogen) - in Amawbia water/leachate, Amaenyi water/leachate, *"Proteus Mirabilis"* (urinary tract pathogen) - in Ifite-Awka water/leachate, Okpuno water/leachate, Amansea water/leachate, *"Klebsiella pneumoniae"* (respiratory pathogen) - in Okpuno water/leachate, Amansea water/leachate, *"Enterobacter aerogenes", "Citrobacter freundii", "Staphylococcus aureus", "Shigella flexneri"* (enteric pathogen). These suggest widespread fecal and environmental contamination, likely from landfill leachate influencing nearby groundwater. Table 2 confirms identifications through Gram staining, catalase (Cat), motility (Mot), indole (Ind), methyl red (MR), Voges-Proskauer (VP), citrate (Cit), and sugar fermentation tests (Lac, Glu, Suc, Fru, Mal), plus oxidase (Oxi) and urease (Ure). All are Gram-negative rods except *"S. aureus"* (Gram-positive cocci). Variations (e.g., "var" for variable results) are noted, supporting standard identifications.

Leachates tend to have higher bacterial loads (average total bacteria: ~1,700 CFU/ml vs. ~1,300 CFU/ml in water), indicating leachate as a contamination source. Coliform levels are similar or slightly higher in leachates (average ~65 CFU/ml vs. ~55 CFU/ml in water, excluding NG). Pathogenic species are shared between paired water and leachate samples, suggesting cross-contamination (e.g., via seepage into groundwater). High counts across all sites point to poor sanitation, landfill mismanagement, or inadequate treatment. WHO guidelines prioritize microbial safety for drinking water, treating groundwater as a potential potable source. Key parameters emphasize absence of fecal indicators to prevent waterborne diseases. Heterotrophic counts are monitored for overall quality but lack strict limits. *"E. coli and Thermotolerant (Fecal) Coliforms"* must be absent (0 CFU/100 ml) in any sample, as they indicate recent fecal contamination and risk of pathogens like those in the data *("E. coli", "Shigella"*). All samples except possibly Amawbia water (if NG = 0 coliforms) exceed this, with counts up to 8,900 CFU/100 ml. Even low-presence species like *"E. coli"* in distributions render samples unsafe (World Health Organization, 2022). Total Coliforms which is not a direct health indicator but signals potential issues if present (>0 CFU/100 ml preferred absence; investigate if >10 CFU/100 ml). All samples with detectable coliforms (e.g., 4,300–8,900 CFU/100 ml) far exceed safe levels, indicating vulnerability to contamination. Heterotrophic Plate Counts (Total Bacteria) showed no numerical limit, but abrupt increases or counts >500 CFU/ml suggest poor quality or regrowth. All samples exceed 500 CFU/ml (up to 2,850 CFU/ml), indicating high risk and need for treatment. None of the samples meet drinking water standards. Water samples are heavily contaminated, likely unsuitable without boiling or filtration. Leachates are even worse, confirming they pose a pollution risk to groundwater [17], [18]. FAO guidelines address irrigation water, especially for crop safety, focusing on microbial risks in wastewater reuse. Groundwater is expected to be cleaner, but standards apply for assessing suitability. Limits are less stringent than WHO's for drinking, emphasizing fecal coliforms to prevent produce contamination.

The data of Fecal Coliforms revealed for unrestricted irrigation (e.g., edible crops eaten raw): ≤1,000 CFU/100 ml (geometric mean) and for restricted irrigation (non-edible or processed crops): ≤100,000 CFU/100 ml. The data's "total coliform" counts include fecal types (e.g., "*E. coli*"), so they serve as proxies. Most samples exceed 1,000 CFU/100 ml (e.g., 4,300–8,900 CFU/100 ml), making them unsuitable for unrestricted use. Some lower counts (e.g., Ifite-Awka water: 4,300 CFU/100 ml) still exceed, while Amawbia water (0 if NG) might comply. Higher leachate counts (e.g., 8,900 CFU/100 ml) pose risks even for restricted irrigation [22]. For Total Bacterial Counts (TBC), there is no specific FAO limit, but high loads correlate with salinity/toxicity issues (not measured here). Elevated counts suggest potential crop stress or pathogen transfer. Presence of enteric bacteria ("*E. coli*", "*Shigella*") increases risks for leafy greens or fruits, requiring mitigation like drip irrigation. Most samples are marginal or unsuitable for unrestricted irrigation due to exceeding fecal coliform thresholds. Leachates are particularly risky, potentially contaminating crops [23]. Water samples might suit restricted irrigation with monitoring, but treatment (e.g., *chlorination*) is recommended.

4. Conclusion

This study confirms that leachate from informal dumpsites in Awka South LGA, Anambra State, significantly contaminates groundwater with microbial pathogens, posing severe risks to public health and environmental sustainability. Across Amawbia, Agu-Awka, Ifite, Okpuno, Amaenyi, and Amansea, groundwater and leachate samples exhibited elevated total bacterial counts (8,900–28,500 CFU/100 ml) and total coliform counts (0–8,900 CFU/100 ml), far exceeding WHO drinking water guidelines (0 CFU/100 ml for "E. coli"/thermotolerant coliforms; <500 CFU/ml for heterotrophic counts). The presence of pathogens like "*Escherichia Coli*", "*Shigella Flexneri*", "*Pseudomonas Aeruginosa*", and "*Klebsiella Pneumoniae*" in both leachate and groundwater indicates direct infiltration, facilitated by permeable sandy-loam soils, fractured aquifers, and high rainfall. These findings highlight the failure of current waste management practices, as unlined dumpsites lack leachate collection systems, exacerbating contamination during the wet season. Non-compliance with WHO and FAO standards renders groundwater unsafe for drinking and marginal for irrigation, risking waterborne diseases like cholera and crop contamination. Urgent interventions are needed, including engineered landfills, leachate treatment systems (e.g., constructed wetlands), regular groundwater monitoring, and community education on safe water practices. By addressing these issues, stakeholders can mitigate microbial pollution, protect vulnerable populations, and align with Sustainable Development Goals (SDGs) 6 (Clean Water and

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Sanitation) and 11 (Sustainable Cities and Communities), ensuring long-term groundwater security in Nigeria and similar tropical regions.

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Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/ or publication of this article.

Data Availability

The datasets generated during and/ or analysed during the current study are available from the corresponding author on reasonable request.

Declaration on AI Use

The authors declare that no artificial intelligence (AI) or AI-assisted tools were used in the preparation of this manuscript.

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