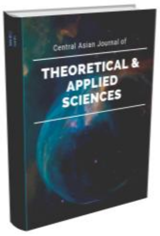

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Article

Microbial Load of Abattoir Effluents and Groundwater Quality in Port Harcourt Metropolis, Rivers State

Amaechi-Onyerimma, C. A.

1. Department of Biology, Ignatius Ajuru University of Education, Port Harcourt, Rivers State, Nigeria
* Correspondence: leobenz@yahoo.com

Abstract: This research investigates the microbiological load of slaughterhouse effluents and the quality of groundwater in Port Harcourt metropolitan, Rivers State, during a 12-month period. Forty-nine water samples (forty-eight groundwater and one surface) were taken from four abattoirs and a control location located 1500 meters from the Iwofe slaughterhouse. Microbial parameters, including Total Heterotrophic Fungi (THF), Total Heterotrophic Bacteria (THB), Hydrocarbon-Utilizing Bacteria (HUB), Hydrocarbon-Utilizing Fungi (HUF), and Vibrio spp., were examined in the laboratory and compared to the control using an experimental and completely randomised design owing to site similarity. The investigation indicated that Woji exhibited a significant THB level (3.1500 CFU g^{-1}), above NSDWQ standards of 0.00 CFU g^{-1} for potable water. The research identified Vibrio spp. at Eliozu (0.0118 CFU g^{-1}) and Eagle Island (0.0150 CFU g^{-1}) during the wet season, indicating substantial public health risks, while increased HUF levels at Iwofe (0.0150 CFU g^{-1}) imply sluggish biodegradation processes that could adversely affect long-term groundwater quality. The study advised, among other recommendations, that the Ministries of Environment and Health ensure the implementation of sustainable waste management practices, such as waste treatment, recycling, and reuse, in all abattoirs to mitigate the release of untreated, reusable, and hazardous wastes that impact human and biodiversity health. Environmentalists and veterinarians must guarantee the implementation of proper sanitary and hygienic procedures in the management of liquid, solid, and gaseous waste produced in abattoirs to mitigate the detrimental impacts of slaughterhouse waste on humans and the ecosystem.

Keywords: Microbial Load, Abattoir Effluents, Groundwater Quality, Port Harcourt Metropolis

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1. Introduction

Abattoirs significantly contribute to environmental contamination, especially when their effluents, laden with organic materials such as blood, faeces, urine, and intestinal contents, are released untreated into the environment. The release of these organic matter effluents fosters pathogenic proliferation and deteriorates the microbiological quality of adjacent groundwater, potentially leading to public health concerns [1], [2]. Eze et al emphasised that when pathogens or organic waste permeate the soil or are carried by runoff during precipitation, they can infiltrate aquifers and contaminate wells and boreholes, particularly in regions with shallow water tables, unprotected boreholes, and permeable geology, thus presenting a significant public health hazard to adjacent communities [3].

A significant problem with slaughterhouse effluents is their elevated microbial burden. The microbial load of slaughterhouse effluents substantially impacts groundwater safety, since released organic waste promotes pathogenic proliferation. Pathogens such as E. coli and Salmonella penetrate shallow, unprotected aquifers, presenting significant public health hazards to adjacent populations [4], [5], [6]. The microbial pollution of groundwater due to slaughterhouse effluents poses a significant public health risk, particularly in underdeveloped countries with inadequate sanitation. Improperly handled organic waste transfers diseases such as E. coli, Salmonella, Vibrio cholerae, and enteric viruses into aquifers, endangering populations reliant on groundwater for drinking and domestic use [7], [8], [9].

Research indicates that groundwater sources near abattoirs frequently display heightened concentrations of total coliforms, faecal coliforms, and other detrimental microorganisms that exceed the acceptable thresholds established by the World Health Organisation (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) worldwide, including Nigeria. Consequently, microbial contamination is most pronounced during the rainy season owing to surface runoff and enhanced leaching, which convey these pathogens into aquifers [10]. Nonetheless, throughout the dry season, the microbial load may persist at elevated levels owing to the continuous buildup of waste and insufficient sanitation measures at slaughter facilities in the Port Harcourt metropolitan. This indicates that the groundwater in the area has heightened concentrations of microbiological pollutants.

Recent research in Nigeria and other regions of sub-Saharan Africa has shown significantly elevated microbial levels in groundwater sources next to slaughterhouse locations. Iwuafor et al. indicated that total coliform and faecal coliform levels in groundwater next to slaughterhouses in southern Nigeria markedly beyond the WHO acceptable thresholds for drinking water. The research conducted by Okoli et al in southern Nigeria indicated that boreholes situated within 200 meters of slaughterhouses exhibited faecal coliform rates above 100 CFU/100 ml, significantly beyond the WHO recommended limit of 0 CFU/100 ml for drinkable water. The data indicate that groundwater is directly affected by the penetration of untreated slaughterhouse effluents, especially in regions with porous soils and elevated water tablesn[11], [12]. Furthermore, throughout the wet season, the danger increases owing to heightened runoff and leaching of microbiological pollutants into groundwater reservoirs.

High microbial loads in groundwater can result in outbreaks of waterborne diseases, including cholera, typhoid fever, dysentery, and gastroenteritis, especially in low-income or peri-urban communities with restricted access to safe drinking water and efficient water treatment systems [13], [14], [15]. Furthermore, the durability of some bacterial spores and viruses in groundwater suggests that even little exposure might result in illness. To alleviate these health hazards, it is essential to implement more stringent hygiene protocols at slaughtering facilities, provide resources for waste treatment infrastructure, and conduct regular monitoring of microbiological indicators in adjacent water sources . Thus, community knowledge, in conjunction with regulatory enforcement, may markedly reduce microbial pollution of groundwater and protect public health.

The ramifications of ingesting microbially tainted groundwater are severe. Increased bacterial concentrations are often linked to outbreaks of waterborne illnesses, such as cholera, typhoid, and dysentery, particularly in populations with restricted access to purified water. Children and immunocompromised persons are more susceptible to illnesses caused by bacteria such as E. coli O157:H7 and Campylobacter jejuni [16], [17]. The continued presence of microbiological pollutants in groundwater systems indicates a deficiency in natural attenuation processes and highlights the need for proactive interventions. Oyelami et al assert that the organic-rich composition of slaughterhouse waste promotes microbial multiplication, but low dissolved oxygen levels and elevated biochemical oxygen demand (BOD) in polluted groundwater impede self-purification mechanisms.

The health consequences of this pollution are substantial. The use of water tainted with pathogens from abattoirs may result in epidemics of waterborne illnesses, including cholera, typhoid fever, gastroenteritis, and dysentery, especially among at-risk groups with restricted access to clean water. The danger increases during the rainy season, when surface runoff and leachate movement are more prominent, facilitating microbial translocation into groundwater systems. Moreover, the detection of microbiological indicators like E. coli not only indicates recent faecal contamination but also implies the potential existence of more resilient and pathogenic organisms, including viruses and protozoa [18], [19], [20]. In the absence of sufficient treatment, such pollutants remain in groundwater, undermining its appropriateness for residential and agricultural use.

Based on these results, it is essential to adopt sustainable waste management methods in abattoirs, including the establishment of waste stabilisation ponds and built wetlands, which have shown efficacy in reducing microbial load prior to discharge. Furthermore, systematic surveillance of groundwater next to abattoirs and public awareness initiatives on the hazards of ingesting untreated water are critical measures for averting disease outbreaks and safeguarding environmental integrity. Therefore, to mitigate hazards, implement legislation, conduct regular groundwater monitoring, establish slaughterhouse effluent treatment systems, and emphasise public health education in rural and peri-urban regions [21], [22]. Olatunji and Bello assert that cleanliness, microbiological risk assessment, and community engagement are essential for safeguarding groundwater in regions affected by abattoirs. This is the essence of the issue.

Statement of the Problem

The unregulated release of slaughterhouse effluents has become a major environmental and public health issue in the Port Harcourt metropolis, Rivers State. Consequently, several abattoirs in the city function without sufficient waste treatment systems, resulting in the direct discharge of organic waste, such as blood, excrement, urine, and decaying tissues, into the adjacent environment. These waste products provide optimal circumstances for the multiplication of pathogenic bacteria, including Escherichia coli, Salmonella spp., Vibrio cholerae, and Shigella spp., which may contaminate groundwater sources via surface runoff and seepage.

Groundwater serves as a major supply of potable water for several urban and peri-urban settlements in Port Harcourt [23], [24], [25]. The proximity of shallow wells and boreholes near slaughterhouses, together with inadequate sanitary infrastructure, increases the danger of microbial contamination. The identification of faecal coliforms and other pathogens in these water sources indicates both contamination and an increased risk of disease outbreaks, including cholera, typhoid fever, and dysentery. Notwithstanding these apprehensions, information about the microbiological health of groundwater next to slaughterhouse sites in Port Harcourt is limited. Furthermore, inadequate enforcement of environmental health standards permits these dangerous activities to persist unregulated. This situation underscores the imperative to assess the microbial load of abattoir effluents and their impact on groundwater quality in the region, a crucial endeavour for informing effective public health interventions, enhancing waste management strategies, and safeguarding the health of residents reliant on these water sources.

This led to the formulation of the subsequent questions that directed this investigation.

What is the mean amount of microbial load from slaughterhouse effluents in groundwater during the rainy season in the research area?

What is the mean amount of microbial load in groundwater from slaughterhouse effluents during the dry season in the research area?

What is the effect of the wet and dry seasons on the microbiological load of slaughterhouse effluents and its influence on groundwater quality in the study area?

Objectives of the Study

The specific objectives of the study are to:

1. Identify the wet season mean quantity of microbial load of abattoir effluents in groundwater in the study area.
2. Determine the dry season mean quantity of microbial load of abattoir effluents in groundwater in the study area.

3. Ascertain the impact of the wet and dry seasons' mean quantity of microbial load of abattoir effluents on groundwater quality in the study area.

Significance of the Study

1. The study would enhance public health and environmental safety by identifying health risks from microbial contamination of groundwater caused by untreated abattoir effluents, promoting awareness of environmental and public health threats.
2. The study would enhance policy and regulatory support by providing evidence-based data to inform effective environmental sanitation policies, regulatory frameworks, and enforcement strategies for waste management.
3. The findings of the study would help to improve waste and water management through emphasis on the need for better abattoir waste treatment systems and regular groundwater quality monitoring to prevent pollution.
4. The study would provide a framework for the conduct of scholarly research for scientific and developmental contributions. In this light, the study contributes to academic knowledge and supports sustainable urban planning through insights into abattoir-related pollution in Port Harcourt metropolis.

2. Materials and Methods

Study Area: The study was carried out in Port Harcourt Metropolis, which includes Port Harcourt and Obio-Akpor Local Government Areas in Rivers State, South-South Nigeria. Geographically, the metropolis is located between latitudes 4°55′N and 6°55′N and longitudes 6°55′E and 7°05′E. Positioned about 25 kilometers from the Atlantic Ocean, the city sits at an elevation of 12 meters above sea level and is situated between the Bonny and Amadi Creeks. According to Uwalaka , Port Harcourt metropolis spans an area of 369 km², consisting of 360 km² of land and 9 km² of water.

Sample Site Location: A total of forty-nine (49) water samples, comprising 48 groundwater and one surface water sample, were collected over 12 months from May 2023 to April 2024 across four abattoir sites in Port Harcourt Metropolis. The sampling process was conducted in four phases. In the first phase, the 12-month study duration was segmented into monthly clusters using a cluster sampling technique. The second phase involved the random selection of four abattoirs, Eagle Island, Eliozu, Egbelu, and Woji, from the twenty identified within the metropolis, while Iwofe abattoir was purposively chosen as the control site for comparative purposes (see Figure 1 for study area and sampling locations). Thirdly, purposive sampling was used to collect one groundwater sample per month from each selected abattoir. In the final phase, purposive sampling was used to obtain a groundwater sample within a 1500 m radius of the Iwofe abattoir, serving as the control point. In total, 12 groundwater samples were collected from each of the four abattoirs (totaling 48), along with one control surface water sample, yielding 49 samples for analysis.

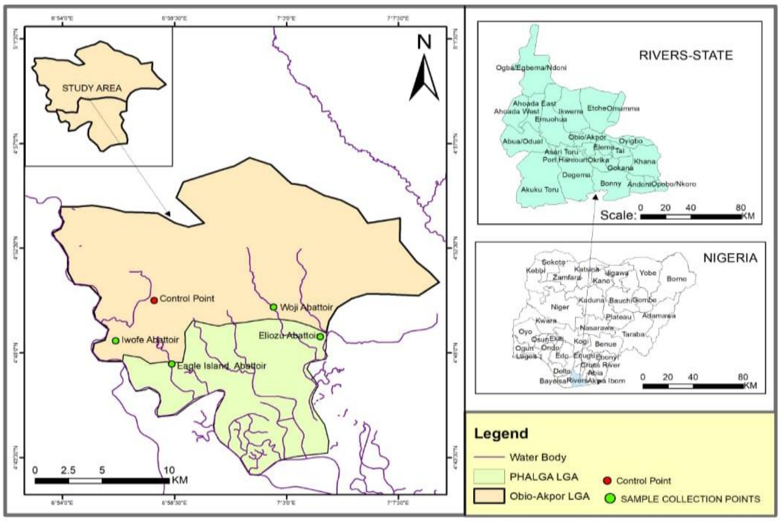

Figure 1. Study Area and Sample Location Map

Research Design: This study adopted an experimental and completely randomized design, which entails the manipulation and control of one or more intervening variables to the subjects, the researcher, experimental instruments, and essential environmental conditions (Nwankwo, 2016).

Method of Data Collection: Groundwater samples were collected monthly over 12 months from four abattoirs and one control site, covering both the wet season (May to October 2023) and dry season. This allowed for seasonal comparison of microbial parameters like Total Heterotrophic Fungi (THF), Total Heterotrophic Bacteria (THB), Hydrocarbon-Utilizing Bacteria (HUB), Hydrocarbon-Utilizing Fungi (HUF), and *Vibrio* spp.

Data Analysis: Relevant statistical tools, including mean, standard error, line charts, bar charts, and other graphical representations, were utilized to analyze the data and effectively address the study's stated objectives.

3. Results and Discussion

Results

Table 1: The wet season mean quantity of microbial load of abattoir effluents in groundwater in the study area

Parameters/Unit	**Abattoir**				**Control**	**NSDWQ (2008) & WHO (2022)**
	Woji	**Iwofe**	**Eliozu**	**Eagle Island**		
THF (CFU G^{-1})	3.1500± 0.00000	0.0000± 0.00000	0.2000± 0.00000	1.1500± 0.00550	0.0000± 0.00000	0.00
THB (CFU G^{-1})	0.53± 0.0025	0.0000± 0.00000	0.0166± 0.00000	0.0667± 0.00000	1.699± 0.00333	3.00
HUB (CFU G^{-1})	0.0000± 0.00000	0.5329± 0.00150	0.4080± 0.00300	0.2979± 0.00230	0.0000± 0.00000	0.00
HUF (CFU G^{-1})	0.0018± 0.00010	0.0027± 0.00010	0.0035± 0.00000	0.0013± 0.00000	0.0017± 0.00010	0.00
Vibrio spp. (CFU G^{-1})	0.0087± 0.00000	0.0028± 0.00010	0.0118± 0.00010	0.0022± 0.00010	0.0017± 0.00000	0.00

Source: Researchers' Fieldwork, 2024.

Table 1 delineates the average microbial loads detected in groundwater samples obtained during the rainy season from four slaughterhouse sites: Woji, Iwofe, Eliozu, and Eagle Island, in addition to a control site located at a considerable distance from direct effluent impact. The evaluated microbiological characteristics are Total Heterotrophic

Fungi (THF), Total Heterotrophic Bacteria (THB), Hydrocarbon-Utilizing Bacteria (HUB), Hydrocarbon-Utilizing Fungi (HUF), and Vibrio spp., quantified in colony-forming units per gramme (CFU g^{-1}). Woji had the highest THF count (3.15 CFU g^{-1}) across the locations, indicating a significant fungal presence possibly because to the buildup of organic-rich trash. Significantly, THF was not detected at either the control or Iwofe locations, indicating localised fungal contamination unique to the Woji slaughterhouse. Eagle Island had the greatest total heterotrophic bacteria (THB) concentration (1.699 CFU g^{-1}), indicating substantial bacterial proliferation presumably supported by nutrient-laden slaughterhouse effluents.The HUB concentrations were highest in Iwofe (0.5329 CFU g^{-1}), decreasing at Eliozu and Eagle Island, suggesting microbial tolerance to hydrocarbon exposure, perhaps due to inadequate effluent or fuel disposal. Conversely, HUF counts were mostly low across all locations, with Eliozu recording the highest number (0.0035 CFU g^{-1}), while the control exhibited insignificant levels. Vibrio spp., known for inducing watery illnesses such as cholera, was identified in all slaughterhouse locations, with Eliozu exhibiting the highest concentration (0.0118 CFU g^{-1}), followed by Woji. Although their numbers are minimal, detection is essential, since neither the WHO nor the NSDWQ permits the presence of Vibrio spp. in potable water.All microbiological characteristics at the control site were undetectable, underscoring the influence of slaughterhouse effluents on microbial contamination at the other locations. The findings indicate an increased risk of groundwater contamination during the rainy season, caused by surface runoff and infiltration, especially in poorly managed slaughterhouse settings. The results emphasise the need for rigorous waste management methods and regular microbiological surveillance to safeguard public health.

Table 2: The dry season mean quantity of microbial load of abattoir effluents in groundwater in the study area

Parameters/Unit	Abattoir				Control	NSDWQ (2008) & WHO (2022)
	Woji	Iwofe	Eliozu	Eagle Island		
THF (CFU G^{-1})	0.7388± 0.00029	0.0000± 0.00000	0.16625± 0.00416	0.21584± 0.00496	0.0000± 0.00000	0.00
THB (CFU G^{-1})	0.5467± 0.00183	0.0000± 0.00000	0.3467± 0.00333	0.1833± 0.00000	2.0142± 0.0025	3.00
HUB (CFU G^{-1})	0.0000± 0.00000	0.0425± 0.00400	0.1573± 0.00165	0.1647± 0.00165	0.0000± 0.00000	0.00
HUF (CFU G^{-1})	0.0000± 0.00000	0.0150± 0.00000	0.0025± 0.00000	0.0012± 0.00000	0.0000± 0.00000	0.00
Vibrio spp. (CFU G^{-1})	0.0000± 0.00000	0.0150± 0.00010	0.0110± 0.00010	0.0150± 0.00010	0.0000± 0.00000	0.00

Source: Researchers' Fieldwork, 2024.

Table 2 shows microbial contamination of groundwater near Port Harcourt abattoirs during the dry season. Parameters assessed include THF, THB, HUB, HUF, and *Vibrio* spp., compared to control sites and NSDWQ (2008)/WHO (2022) standards, which recommend zero presence of pathogenic or indicator organisms in drinking water. Woji recorded the highest Total Heterotrophic Fungi (THF) load (0.7388 CFU g^{-1}), while Iwofe showed none. Eliozu (0.16625 CFU g^{-1}) and Eagle Island (0.21584 CFU g^{-1}) had moderate levels. Control sites met NSDWQ/WHO standards, indicating that abattoir effluent likely caused the fungal contamination. Similarly, Total Heterotrophic Bacteria (THB) levels were highest at Woji (0.5467 CFU g^{-1}), followed by Eliozu (0.3467 CFU g^{-1}) and Eagle Island (0.1833 CFU g^{-1}). Iwofe and control showed none. Though below NSDWQ/WHO limits, their presence suggests possible fecal or organic contamination.

Also, Eliozu (0.1573 CFU g^{-1}) and Eagle Island (0.1647 CFU g^{-1}) showed the highest Hydrocarbon-Utilizing Bacteria (HUB) levels, while Woji had none. Iwofe had minimal presence, and control showed none, indicating pollution likely from the abattoir or related human activities. For Hydrocarbon-Utilizing Fungi (HUF), only Iwofe (0.0150 CFU g^{-1}), Eliozu (0.0025 CFU g⁻¹), and Eagle Island (0.0012 CFU g⁻¹) showed minimal HUF presence, while Woji and control had none, indicating limited hydrocarbon contamination in affected locations. While low levels of *Vibrio* spp. were detected in Iwofe (0.0150 CFU g⁻¹), Eliozu (0.0110 CFU g⁻¹), and Eagle Island (0.0150 CFU g⁻¹), but were absent in Woji and control samples. Their presence poses public health risks due to the waterborne disease potential. Overall, groundwater near abattoirs in Woji, Eliozu, and Eagle Island showed microbial contamination exceeding safe limits, unlike the uncontaminated control sites. This confirms abattoir effluent impacts, emphasizing the need for wastewater management and regular groundwater monitoring to protect public health

Table 3: The impact of the wet and dry seasons mean quantity of microbial load of abattoir effluents on groundwater quality in the study area

Parameters/Unit	Abattoir								Control		NSDWQ (2008)
	Woji		Iwofe		Eliozu		Eagle Island				
	WET	DRY	WET	DRY	WET	DRY	WET	DRY	WET	DRY	
THB (CFU G-1)	3.1500 ±0.00000	0.7388 ±0.0029	0.0000 ±0.00000	0.0000 ± 0.00000	0.2000 ±0.00000	0.16625±0.00416	1.1500 ±0.00550	0.21584±0.00496	0.0000 ±0.00000	0.0000 ±0.00000	0.00
THF (CFU G-1)	0.53±0.0025	0.5467 ± 0.00183	0.0000 ± 0.00000	0.0000 ± 0.00000	0.0166 ±0.00000	0.3467 ±0.00333	0.0667 ±0.00000	0.1833 ±0.00000	1.699± 0.00333	2.0142 ±0.0025	3.00
HUB (CFU G-1)	0.0000 ±0.00000	0.0000 ± 0.00000	0.5329 ±0.00150	0.0425 ±0.00400	0.4080 ±0.00300	0.1573 ±0.00165	0.2979 ±0.00230	0.1647 ±0.00165	0.0000 ±0.00000	0.0000 ± 0.00000	0.00
HUF (CFU G-1)	0.0018 ± 0.00010	0.0000 ± 0.00000	0.0027 ±0.00010	0.0150 ± 0.00000	0.0035 ±0.00000	0.0025 ± 0.00000	0.0013 ±0.00000	0.0012 ± 0.00000	0.0017 ±0.00010	0.0000 ± 0.00000	0.00
Vibrio spp. (CFU G-1)	0.0087 ± 0.00000	0.0000 ± 0.00000	0.0028 ± 0.00010	0.0150 ± 0.00010	0.0118 ± 0.00010	0.0110 ± 0.00010	0.0022 ± 0.00010	0.0150 ± 0.00010	0.0017 ± 0.00000	0.0000 ± 0.00000	0.00

Source: Researchers' Fieldwork, 2024.

Table 3 compares wet and dry season mean microbial loads in groundwater near abattoirs in Woji, Iwofe, Eliozu, and Eagle Island, using control samples and NSDWQ (2008) standards as benchmarks. Total Heterotrophic Bacteria (THB) levels were higher in the wet season across all abattoir sites, with Woji showing the highest (3.1500 CFU g⁻¹), exceeding NSDWQ limits. Eliozu and Eagle Island also had elevated values. Dry season levels dropped, especially in Iwofe and control samples. This indicates that runoff and effluent infiltration increase microbial contamination during the wet season. Total Heterotrophic Fungi (THF) levels were higher during the dry season in Eliozu (0.3467 CFU g⁻¹) and Eagle Island (0.1833 CFU g⁻¹), while Woji had similar values in both seasons. Iwofe and control showed no fungi, except a slight wet-season rise. This suggests seasonal fungal growth due to organic buildup and reduced degradation in dry periods.

Hydrocarbon-Utilizing Bacteria (HUB) levels peaked in the wet season at Iwofe (0.5329 CFU g⁻¹), Eliozu (0.4080 CFU g⁻¹), and Eagle Island (0.2979 CFU g⁻¹), but declined in the dry season. Woji and control showed none, indicating runoff-driven hydrocarbon contamination from abattoir waste, contributing to groundwater pollution. Also, Hydrocarbon-Utilizing Fungi (HUF) levels were low across all sites, slightly higher in the wet season at Iwofe and Eliozu. Their presence indicates minor hydrocarbon contamination, influenced by seasonal moisture and nutrient availability. While pathogenic *Vibrio* species were found at low but notable levels during the wet season in all abattoir sites except Woji, with the highest levels in Iwofe and Eagle Island. Their presence, especially in the wet season, poses public health risks due to links with waterborne gastrointestinal infections.

Discussion of Findings

Table 1 shows significant microbial contamination of groundwater near abattoirs, especially during the wet season. Elevated levels of THF, THB, HUB, HUF, and *Vibrio* spp. indicate public health risks. Woji's high THF level (3.15 CFU/g) suggests intense fungal growth from decomposing organic waste. This finding is in agreement with Olanrewaju et al. that the presence of fungi in groundwater can lead to allergic reactions and opportunistic infections, particularly among immunocompromised individuals. The complete absence of THF in both the control and Iwofe sites suggests that the contamination is localized and directly related to effluent discharge.

THB counts, notably high at Eagle Island (1.699 CFU/g), indicate excessive bacterial activity. This exceeds safe thresholds *and* aligns with findings by Akinbile and Yusoff , who emphasized that bacterial indicators like THB are reliable predictors of fecal and organic pollution in groundwater. The proliferation of these bacteria suggests a high nutrient load from organic waste, which poses a risk of gastrointestinal illnesses for users of untreated groundwater. The detection of *Hydrocarbon-Utilizing Bacteria (HUB)*, with Iwofe recording the highest value (0.5329 CFU/g), points to contamination by petroleum-based substances, possibly from meat processing tools cleaned with petroleum derivatives or nearby hydrocarbon spills. Research by Eze and Nwachukwu notes that such microbes indicate chronic exposure of aquifers to hydrocarbons, which can compromise the ecological integrity of subsurface water.

High THB counts at Eagle Island (1.699 CFU/g) indicate bacterial contamination, exceeding safe limits, and align with findings by Akinbile and Yusoff , who emphasized that THB to fecal and organic pollution. This suggests nutrient-rich waste that risks gastrointestinal illness. HUB presence, highest at Iwofe (0.5329 CFU/g), implies petroleum contamination, possibly from abattoir activities. Eze and Nwachukwu highlight HUB as indicators of chronic hydrocarbon exposure, threatening subsurface water quality and ecological stability. These findings underscore the public health and environmental risks of abattoir-related groundwater pollution.

Although HUF levels were relatively low across sites, Eliozu recorded the highest (0.0035 CFU/g), indicating persistent exposure to organic pollutants. Studies by Okoro et al have shown that even low HUF concentrations can affect water palatability and microbial balance. The presence of *Vibrio* spp., especially at Eliozu (0.0118 CFU/g) and Woji (0.0087 CFU/g), is concerning. *Vibrio cholerae*, a known pathogen, poses serious health risks. According to WHO and NSDWQ , drinking water must be free of *Vibrio*. Their presence signals a high risk of disease, especially during wet-season runoff. In contrast, the control site showed zero microbial counts, indicating abattoir activities as the main contamination source. This supports Ayandele and Adebiyi's findings linking unregulated abattoir waste to groundwater pollution in urban Nigerian areas.

Table 2 shows dry season mean concentrations of microbial indicators, THF, THB, HUB, HUF, and *Vibrio* spp., in groundwater from four abattoir sites, compared to a control. Values are assessed against NSDWQ and WHO standards, which mandate zero microbial presence in drinking water. Total Heterotrophic Fungi (THF) levels peaked at Woji, with moderate values at Eagle Island and Eliozu; Iwofe and the control had none. Their presence, though lower than in the wet season, indicates persistent contamination and health risks for immunocompromised individuals. Also, Total Heterotrophic Bacteria (THB) levels were highest at Woji and Eliozu, indicating continued bacterial contamination in the dry season. The control site's elevated THB suggests unrelated contamination. Thus, abattoir site values exceeded safe limits, posing potential waterborne infection risks for the water consumers.

Hydrocarbon-Utilizing Bacteria (HUB) were found at Eliozu, Eagle Island, and Iwofe, but were absent at Woji and the control site, indicating possible petroleum waste infiltration from maintenance or animal-processing activities. Eze and Nwachukwu identify HUB as markers of hydrocarbon contamination. HUF levels were minimal, highest at Iwofe (0.0150 CFU g^{-1}), suggesting slow biodegradation or adaptation, potentially affecting long-term water quality. Also, the detection of *Vibrio* spp., a pathogen causing cholera and other gastrointestinal diseases, at Iwofe (0.0150 CFU g^{-1}), Eliozu (0.0110 CFU g^{-1}), and Eagle Island (0.0150 CFU g^{-1}) is alarming. WHO and NSDWQ prohibit the presence of *Vibrio* in drinking water. Even low levels signal fecal or organic contamination and poor sanitation, especially during the dry season when dilution is minimal. Notably, all microbial parameters were absent at the control site, confirming that contamination at abattoir sites is linked to their waste discharge.

Table 3 shows seasonal variation in microbial loads of groundwater from abattoirs in Woji, Iwofe, Eliozu, and Eagle Island, compared with a control site and NSDWQ (2008) standards across five key microbial parameters. The findings show significantly higher microbial concentrations during the wet season, particularly for THB and HUB, indicating increased infiltration and surface runoff of organic and petroleum-based wastes from abattoirs into groundwater systems. For instance, Woji recorded an exceptionally high THB level during the wet season (3.1500 CFU g^{-1}), which far exceeds the NSDWQ safe limit of 0.00 CFU g^{-1} for drinking water. This supports the conclusion that rainfall and runoff during the wet season substantially exacerbate groundwater contamination through leaching of abattoir waste materials .

Moreover, the consistent detection of *Vibrio* spp., particularly in the wet season at Eliozu (0.0118 CFU g^{-1}) and Eagle Island (0.0150 CFU g^{-1}), raises serious public health concerns. *Vibrio cholerae*, the causative agent of cholera, is waterborne and thrives in moist environments with high organic content . According to the World Health Organization, the presence of *Vibrio* in potable water is unacceptable, even in trace amounts. Their detection in this study underscores the vulnerability of shallow aquifers to pathogenic intrusion, particularly during the rainy season. Additionally, the presence of Hydrocarbon-Utilizing Bacteria (HUB) and Fungi (HUF), especially in Iwofe and Eliozu, also signifies possible hydrocarbon pollution. These microbes are known to metabolize petroleum-based compounds and often appear in contaminated aquifers near industrial or waste-disposal zones .

Furthermore, the occurrence of microbes, even in low concentrations, indicates chronic exposure of groundwater to petroleum derivatives, likely from the cleaning of tools or machinery associated with abattoir operations. This aligns with findings by Okoro et al who observed that low-level presence of HUF in groundwater may lead to microbial succession changes, affect palatability, and compromise long-term water safety. Interestingly, the control site maintained zero or near-zero values across all microbial indicators, reaffirming that the contamination is localized and primarily linked to effluent discharge from abattoirs. This observation supports earlier conclusions by Ayandele and Adebiyi, who reported that poorly regulated abattoir operations significantly contribute to microbiological degradation of groundwater in urban Nigerian communities.

4. Conclusion

In summary, despite lower dry season microbial levels, the presence of pathogens and pollutant-tolerant organisms indicates ongoing contamination, highlighting the urgent need for better waste management, water source monitoring, and groundwater protection enforcement. Thus, the data show seasonal groundwater contamination near abattoirs, with higher microbial loads in the wet season from runoff and leaching. Safe control values confirm human-related sources, emphasizing the need for improved waste management and seasonal monitoring to protect public health.

The seasonal comparison shows that rainfall and abattoir activity significantly impact groundwater contamination, with higher microbial loads in the wet season increasing disease and pollution risks. This underscores the need for stronger waste management, regulations, and continuous microbial monitoring to protect public health, especially in the study area. In conclusion, the results underscore the urgent need for enhanced sanitary practices, regulated waste treatment in abattoirs, and regular groundwater quality monitoring to protect public health and ensure safe water access in Port Harcourt and similar urban regions.

Recommendations

Based on the findings of the study, the following recommendations were made:

1. The Ministries of Environment and Health should ensure that sustainable waste management practices like waste treatment, recycling, and reuse are adopted in strategic abattoirs to reduce the discharge of untreated, reusable, and harmful wastes that harm human and biodiversity health.
2. Environmentalists and veterinarians should ensure that good sanitary and hygienic practices are adopted in managing the liquid, solid, and gaseous waste generated in abattoirs in order to minimize the harmful effects of abattoir wastes on both man and the ecosystem.
3. The government and environmental health agencies enforce proper abattoir waste treatment systems and implement seasonal groundwater quality monitoring to prevent public health risks and aquifer pollution in the Port Harcourt metropolis.

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