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EGYPTIAN ACADEMIC JOURNAL OF

BIOLOGICAL SCIENCES

PHYSIOLOGY & MOLECULARBIOLOGY

ISSN
2090-0767

WWW.EAJBS.EG.NET

Vol. 16 No. 2 (2024)

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Citation: *Egypt.Acad.J.Biolog.Sci. (C.Physiology and Molecular biology) Vol. 16(2) pp113-127 (2024)*

DOI: 10.21608/EAJBSC.2024.375165

Egypt. Acad. J. Biolog. Sci., 16(2):113-127 (2024)

Egyptian Academic Journal of Biological Sciences
C. Physiology & Molecular Biology
ISSN 2090-0767
www.eajbsc.journals.ekb.eg

Physicochemical Properties of Water Samples in the Volta Region of Ghana: Implications for Public Health

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ARTICLE INFO
Article History
Received:17/7/2024
Accepted:21/8/2024
Available:25/8/2024

Keywords:
Water quality, physicochemical properties, WHO guidelines, public health, Ghana.

ABSTRACT

Bachground: Access to safe drinking water is vital for public health, yet water sources in many developing countries, including Ghana, are often contaminated. This study assessed physicochemical properties of water samples from various sources in Ghana's Volta Region against WHO recommendations.**Methodology:** A cross-sectional study collected 104 water samples from wells, taps, boreholes, streams, and rainwater in Ho and surroundings from September 2021 to September 2022. Analyzed parameters included pH, total suspended and dissolved solids, ammonia, nitrate, phosphate, sulphate, fluoride, alkalinity, hardness, calcium, and magnesium.**Results:** 78.8% of samples were moderate to very hard. Median ammonia (46.2381 mg/L) and phosphate (12.2437 mg/L) levels exceeded WHO recommendations. 38.46% of samples had fluoride concentrations above WHO limits. Seasonal variations showed higher ammonia and phosphate levels during the dry season.**Conclusion:** Elevated ammonia, phosphate, fluoride, and elevated water hardness levels highlight the need for effective water treatment and management. Seasonal variations emphasize the importance of regular monitoring and targeted interventions. These findings inform evidence-based decision-making for public health interventions in the region.

INTRODUCTION

The UN General Assembly Resolution 64/292 of 2010 posits that “the right to safe and clean drinking water and sanitation is a human right essential for the full enjoyment of life and all human rights” (United Nations, 2010). However, water sources in many developing countries, including Ghana, are often contaminated and do not get treated properly for domestic consumption.

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The World Health Organization (WHO) estimates that 785 million people worldwide lack access to basic drinking water services, and 2 billion people use a drinking water source contaminated with faeces (WHO, 2019). In Ghana, despite significant progress in recent years, only 16% of the population have access to safely managed drinking water services (United Nations, 2022).

The physicochemical properties of water can significantly impact its quality and suitability for human consumption. These properties include pH, total suspended solids (TSS), total dissolved solids (TDS), turbidity, and the presence of various chemical contaminants such as ammonia, nitrate, phosphate, sulphate, fluoride, and heavy metals. Elevated levels of these parameters pose serious health risks and contribute to the deterioration of water quality. For instance, high levels of ammonia in drinking water can cause irritation to the eyes, nose, and throat, and can be particularly harmful to infants, leading to a condition known as methemoglobinemia or "blue baby syndrome" (Mukherjee *et al.,* 2015). Similarly, excessive fluoride intake from drinking water can lead to dental and skeletal fluorosis, a condition characterized by the mottling of teeth and the weakening of bones (Ganta *et al.,* 20115; Kumar & Sharma, 2011).

Despite the importance of monitoring and maintaining the physicochemical quality of water sources, there is limited data available on the specific characteristics of water in many regions of Ghana. This lack of information hinders the development and implementation of effective water treatment and management strategies, potentially exposing the population to contaminated water and associated health risks. A previous study has examined groundwater quality in some districts of the eastern region of Ghana (Fianko *et al.,* 2010). It found that anthropogenic activities were having a significant impact on groundwater quality. Specifically, high concentrations of chloride and total dissolved solids were found in wells in high residential areas, while the highest levels of sodium, calcium, sulphate, and nitrate were found in agricultural and high-density residential areas. They also reported that about 50% of boreholes sampled had elevated levels of nitrate-nitrogen, which was attributed to agricultural runoff (Fianko *et al.,* 2010). In a more recent study, Anornu *et al.,* (2017) used isotopic and hydrochemical techniques to trace sources of groundwater nitrate contamination in the Upper East Region of Ghana. Their findings revealed that nitrate concentrations varied widely, with many samples exceeding baseline values. The main source of nitrate was identified as manure from both human and animal waste. Interestingly, they also found a relationship between higher nitrate levels and younger groundwater. The study highlighted potential health risks from nitrate contamination, particularly for children. These insights from previous research demonstrate that water quality issues, particularly related to anthropogenic contamination and elevated nitrate levels, have been identified in different parts of Ghana. This context provides a clear rationale for further study of physicochemical properties of water sources, particularly in other underserved regions of Ghana, such as the Volta Region. (Anornu *et al.,* 2017; Fianko *et al.,* 2010; Gyau-Boakye & Dapaah-Siakwan, 1999), but there is a need for more comprehensive and up-to-date assessments, particularly in underserved regions like the Volta Region.

The aim of this study was to assess the physicochemical properties of water samples collected from various sources in the Volta Region of Ghana and evaluate how they align if they meet the with World Health Organization (WHO) guidelines and to inform public health interventions and water quality management efforts in the region.

MATERIALS AND METHODS

Study Design, Study Area, Sample Distribution And Collection:

A cross-sectional study was used in carrying out this study. One hundred and four

(104) water samples were collected aseptically from chosen sites in Ho and its' surroundings (Fig. 1) from September 2021 to September 2022 in the following proportions; 34 direct tap water (32.69%), 27 stored tap water (25.96%), 17 well water (16.35%), 19 borehole water (18.27%), 5 stream water (4.81), and 2 samples of rain water (1.92). Samples taken between January and April constituted the dry season samples while those taken from May to the early part of November constituted the wet season samples. 750mLs of water samples was collected from various sources, including wells, taps, boreholes, streams, and rainwater, using sterile containers. For well water, a sterile bottle was securely tied with a thread and lowered into the well without touching the walls, filled underwater, and raised back up. Tap water was sampled directly after running the tap for 2 minutes to clear stagnant water. Stored tap water was collected by agitating the container, carefully filling the bottle underwater, and sealing it before removal. Water was sampled directly from borehole after running it for 2 minutes to clear stagnant water. Stream water was collected by submerging the bottle upstream and filling it underwater. Rainwater was collected directly into a sterile, wide-mouthed bottle placed on a surface protected from runoff. All samples were sealed, labelled, and transported on ice to maintain a cool temperature until laboratory analysis. All samples were collected in duplicate. The physicochemical parameters of water samples were investigated at the Water and Sanitation Laboratory of the University of Cape Coast, Ghana.

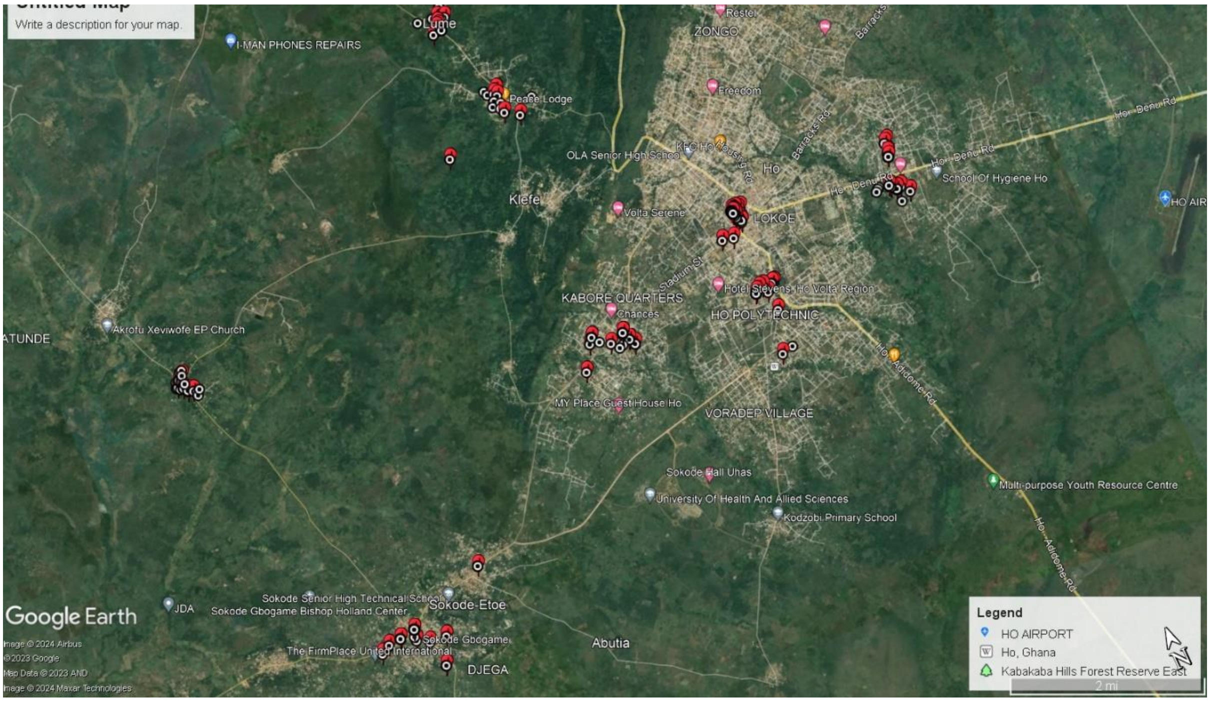


Fig. 1: Geospatial distribution of water samples collected.

Analysis of Sample:

Analysis of the water samples was done in accordance with the procedures suggested in the standard analytical procedure manual (Table 1) (APHA, 2012). The parameters, methodology adopted and equipment used have been listed in Table 1. Figure 2 shows a flow chart of the methodology employed in this study.

Table 1: Methods of analysis of samples**.**

s/no	Parameter	Method used and equipment
1	pH	Potentiometric; Eutech PC 700 bench top meter
2	Total Dissolved Solids (TDS)	Potentiometric; Eutech PC 700 bench top meter
3	Ammonia- Nitrogen (NH4+)	Nesslerization method; UV-VIS spectrophotometer
4	Nitrate- Nitrogen (NO_3^-- N)	UV- Spectrophotometric; UV-VIS spectrophotometer
5	Phosphate (PO^{3-}_4 – P)	Ascorbic acid method; UV-VIS spectrophotometer
6	Sulphate (SO_4^{2-})	Turbidimetric method; UV-VIS spectrophotometer
7	Fluoride (F^-)	SPADNS method; UV-VIS spectrophotometer
8	Total Alkalinity	Titration
9	Total Hardness	EDA titrimetric method
10	Calcium	Titration
11	Magnesium	Titration

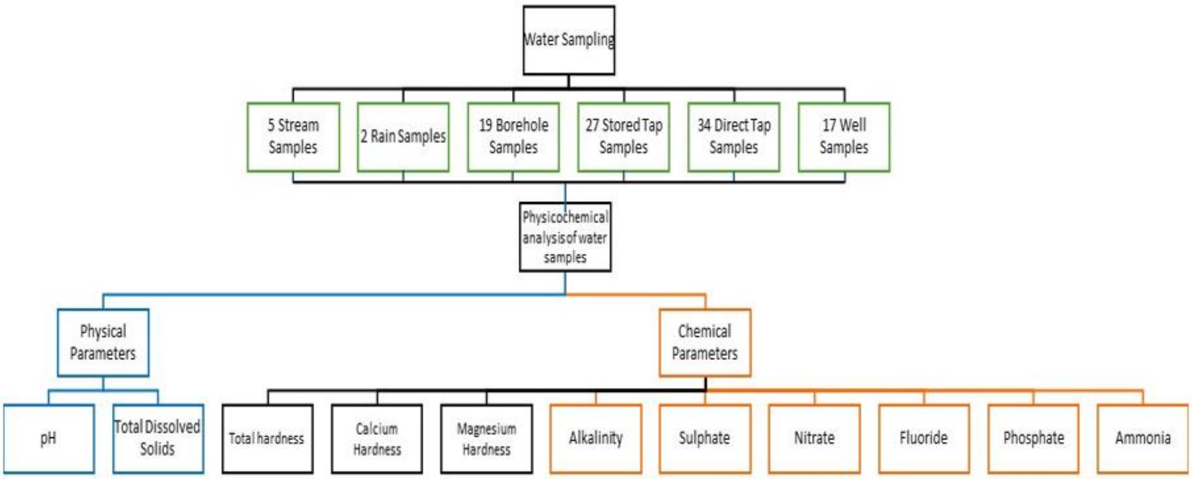


Fig. 2: Flow chart of study procedure

Quality Assurance of Physicochemical Analysis:

To ensure the accuracy and reliability of the results, all measurements were performed in triplicate (Duru *et al.*, 2019), and the average value of each set of results was used for the analysis. Prior to the study, all instruments were calibrated using standard solutions of known concentrations (APHA, 2012). For each ion under investigation, a calibration curve was constructed by analysing a series of standard solutions with known concentrations. These calibration curves were then employed to determine the concentrations of the analyte in the water samples. The value for each analyte was obtained by calculating the average of three replicate measurements. To account for any potential background interference or contamination, blank samples were prepared and subjected to the same analytical procedures as the actual samples.

Data Analysis:

The data was compiled in Microsoft Excel and analysed using IBM SPSS Statistics 26. Due to the non-normal distribution of the dataset, descriptive statistics for quantitative variables were reported using median and interquartile range. The descriptive statistics for the categorical and the quantitative variables were reported. Statistical significance was set at P < 0.05. Statistical methods such as the Kruskal-Wallis test was used to analyse differences in physicochemical properties across various water sources and between seasons. Correlation analysis was performed to examine relationships between different physicochemical parameters. Graphical displays such as bar graphs were used where appropriate to describe data.

RESULTS

The analysis of the physicochemical properties of the water samples revealed several significant findings (Table 2). The median ammonia and phosphate levels exceeded the WHO recommendations, with values of 46.2381 mg/L (interquartile range: 18.3889-101.6825 mg/L) and 12.2437 mg/L (interquartile range: 1.4673-24.5775 mg/L), respectively. These values are significantly higher than the WHO permissible levels of 1.5 mg/L for ammonia and 0.3 mg/L for phosphate (WHO, 2008, 2011).

Table 2: Analysis of physicochemical properties of water samples.

s/n	Parameters	Median	Interquartile range		WHO permissible level (WHO, 2008)	p-value
			25%	75%		
1	**Ammonia (mg/L)**	46.2381	18.3889	101.6825	1.5	**<0.05**
2	**Sulphate (mg/L)**	0.0513	0.013	0.1354	250	**<0.05**
3	**Phosphate (mg/L)**	12.2437	1.4673	24.5775	0.3	**<0.05**
4	**Nitrate (mg/L)**	0.5333	0.4799	0.6903	50	**<0.05**
5	**Calcium Hardness (mg/L $CaCO_3$)**	16.3126	13.3466	20.7614	200	**<0.05**
6	**Total Hardness (mg/L)**	119.4892	96.2	176.5775	500	**<0.05**
7	**Alkalinity (mg/L $CaCO_3$)**	41.5	34	46	30-400	Within range
8	**pH**	6.91	6.77	7.09	6.5-8.5	Within range
9	**Total Dissolved Solids (mg/L)**	16.8333	13.2667	18.2917	500	**<0.05**
10	**Magnesium(mg/L)**	24.8315	18.7021	36.8968		
11	**Fluoride(mg/L)**	0.6276	0	2.3747	1.5	0.34

mg/L= milligrams per litre; pH= power of Hydrogen; p value is significant at $p \leq 0.05$. P value was generated using the Wilcoxon Signed Rank Test. No specific health-based guideline value from WHO for Magnesium.

The pH values of the water samples ranged from 3.85 to 8.76, with a median pH of 6.91 (interquartile range: 6.77-7.09). While most samples fell within the WHO acceptable range of 6.5 to 8.5 (Table 1), the presence of acidic water in some sources is a concern. Most water samples (52.9%) fell within the moderately hard category, with a significant proportion (21.2%) classified as very hard ($p < 0.001$) (Table 3). Fluoride concentrations on the other hand were above the WHO acceptable limit of 1.5 mg/L in 38.46% of the samples tested (Table 4).

Table 3: Analysis of the categories of water hardness.

Categories of hardness (WHO, 2022)	Frequency	median	No. of samples ≤ median	No. of samples > median	Percentile		p-value
					25%	75%	
Moderately hard (60.1-120mg/L)	55	96.2	28	27	92.5	114.7	<0.001
Hard (120.1-180mg/L)	27	125.8	18	9	122.1	145.8	
Very hard (>180mg/L)	22	381	12	10	333	510.6	

p-value = Median of moderate vrs hard vrs very hard

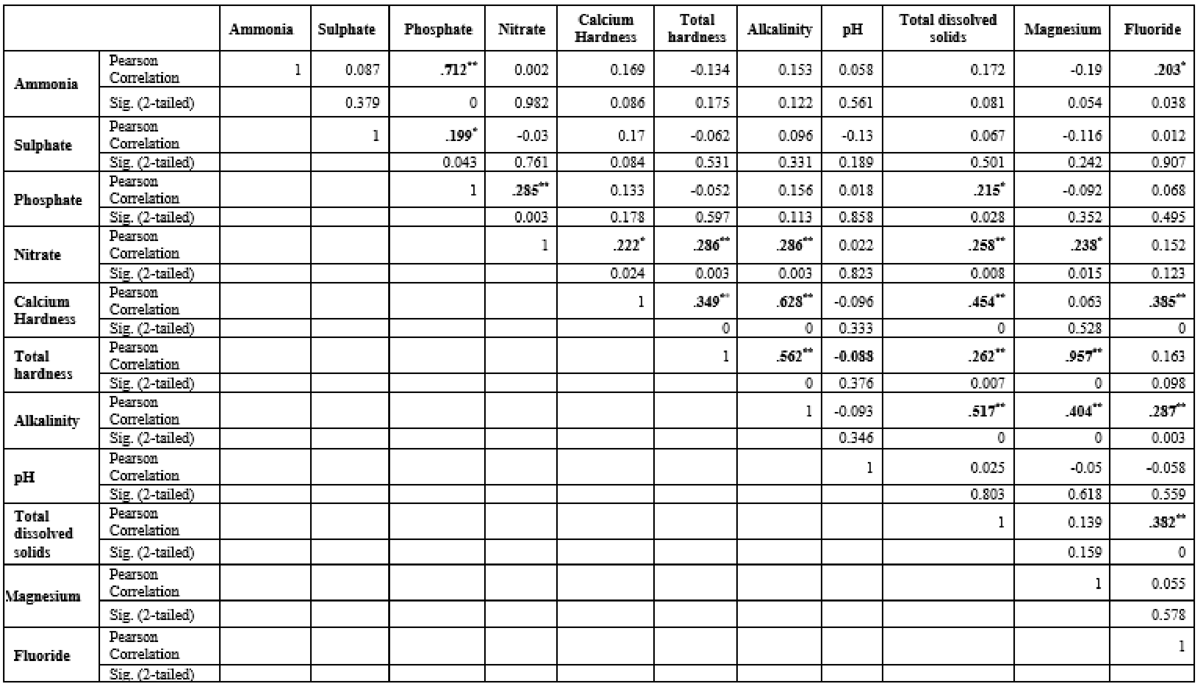
Table 4: Analysis of fluoride concentration**.**

Fluoride concentration(WHO, 2017)	**Frequency**	**Median**	**No. of samples ≤ median**	**No. of samples > median**	**Percentile**		**p-value**
					25%	**75%**	
Within acceptable limit (≤1.5mg/L)	64	0	52	12	0	0.5958	<0.001
Above acceptable limit (>1.5mg/L)	40	3.12	0	40	2.2379	4.7958	

p-value = Acceptable vrs Above acceptable

The correlation analysis (Table 5) revealed strong positive associations between ammonia and phosphate levels (r=0.712, p<0.01), suggesting a common source or related underlying process contributing to the presence of these nutrients in the water samples.

Table 5: Correlation between the various physicochemical properties of water samples.



		Ammonia	**Sulphate**	**Phosphate**	**Nitrate**	**Calcium Hardness**	**Total hardness**	**Alkalinity**	**pH**	**Total dissolved solids**	**Magnesium**	**Fluoride**
Ammonia	Pearson Correlation	1	0.087	**.712****	0.002	0.169	-0.134	0.153	0.058	0.172	-0.19	**.203***
	Sig. (2-tailed)		0.379	0	0.982	0.086	0.175	0.122	0.561	0.081	0.054	0.038
Sulphate	Pearson Correlation		1	**.199***	-0.03	0.17	-0.062	0.096	-0.13	0.067	-0.116	0.012
	Sig. (2-tailed)			0.043	0.761	0.084	0.531	0.331	0.189	0.501	0.242	0.907
Phosphate	Pearson Correlation			1	**.285****	0.133	-0.052	0.156	0.018	**.215***	-0.092	0.068
	Sig. (2-tailed)				0.003	0.178	0.597	0.113	0.858	0.028	0.352	0.495
Nitrate	Pearson Correlation				1	**.222***	**.286****	**.286****	0.022	**.258****	**.238***	0.152
	Sig. (2-tailed)					0.024	0.003	0.003	0.823	0.008	0.015	0.123
Calcium Hardness	Pearson Correlation					1	**.349****	**.628****	-0.096	**.454****	0.063	**.385****
	Sig. (2-tailed)						0	0	0.333	0	0.528	0
Total hardness	Pearson Correlation						1	**.562****	**-0.088**	**.262****	**.957****	0.163
	Sig. (2-tailed)							0	0.376	0.007	0	0.098
Alkalinity	Pearson Correlation							1	-0.093	**.517****	**.404****	**.287****
	Sig. (2-tailed)								0.346	0	0	0.003
pH	Pearson Correlation								1	0.025	-0.05	-0.058
	Sig. (2-tailed)									0.803	0.618	0.559
Total dissolved solids	Pearson Correlation									1	0.139	**.382****
	Sig. (2-tailed)										0.159	0
Magnesium	Pearson Correlation										1	0.055
	Sig. (2-tailed)											0.578
Fluoride	Pearson Correlation											1
	Sig. (2-tailed)											

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

The Kruskal-Wallis test was used to analyse the differences in physicochemical properties across various water sources by comparing the medians for boreholes, direct tap water, stored tap water, rainwater, streams, and wells. Ammonia levels differed significantly (p=0.003), with the highest median in stream water (130.37mg/L) and the lowest in rainwater (32.06 mg/L). Phosphate levels also varied significantly (p=0.004), being lower for boreholes (1.52 mg/L) and rainwater (8.83 mg/L) compared to stream water (30.45 mg/L). Nitrate exhibited a significant difference (p=0.012), with the highest median in stream water (1.53 mg/L) compared to rainwater (0.65 mg/L). Calcium hardness differed markedly (p=0.014), with stream samples having the highest median (100.38 mg/L) as against the lowest in rainwater (14.81 mg/L). Parameters like alkalinity, pH, and fluoride did not show statistically significant differences in their medians across the water sources. Table 6 below provides further details.

Table 6: Analysis of physicochemical properties across the various water sources.

Physicochemical properties	Water type	Number of samples	Median	Interquartile range		p-value
				25th	75th	
Ammonia	borehole	19	19.8889	13.2222	33.1587	0.003
	direct tap	34	46.24	21.9524	101.6825	
	stored tap	27	57.48	17.7143	127.5079	
	rain	2	32.06	9.4881	38.6071	
	stream	5	130.37	111.2381	149.6508	
	well	17	92.75	27.5079	104.4365	
Sulphate	borehole	19	0.03	0.0092	0.0636	0.008
	direct tap	34	0.03	0.0116	0.1084	
	stored tap	27	0.11	0.0389	0.1740	
	rain	2	0.29	0.0477	0.3810	
	stream	5	0.13	0.1138	0.1950	
	well	17	0.05	0.0185	0.1238	
Phosphate	borehole	19	1.52	1.0343	9.8863	0.004
	direct tap	34	9.89	1.3831	22.5234	
	stored tap	27	17.19	9.3311	29.8862	
	rain	2	8.83	1.1005	12.1505	
	stream	5	30.45	19.8028	33.0567	
	well	17	18.08	6.5308	24.5234	
Nitrate	borehole	19	0.53	0.479	0.6003	0.012
	direct tap	34	0.53	0.4790	0.6003	
	stored tap	27	0.53	0.3759	0.6141	
	rain	2	0.65	0.4502	0.5177	
	stream	5	1.53	1.3200	2.0042	
	well	17	0.53	0.5057	1.9809	
Calcium hardness	borehole	19	14.8296	11.3807	19.2785	0.014
	direct tap	34	16.31	11.8637	19.2785	
	stored tap	27	16.31	13.3466	31.2459	
	rain	2	14.81	10.0100	12.2089	
	stream	5	100.38	89.2159	121.4307	
	well	17	17.80	12.6052	114.7000	
Total hardness	borehole	19	97.20	92.2	122.1	0.023
	direct tap	34	125.80	96.2000	333.0000	
	stored tap	27	118.40	113.7750	126.1250	
	rain	2	86.20	59.9250	69.3750	
	stream	5	111.28	98.5500	131.0563	
	well	17	122.10	116.2478	357.0500	
Alkalinity	borehole	19	41.00	33.0000	47.0000	0.666
	direct tap	34	42.00	33.0000	45.0000	
	stored tap	27	40.00	37.0000	43.2500	
	rain	2	44.00	30.7500	35.2500	
	stream	5	47.00	36.0000	107.0000	
	well	17	42.00	30.0000	84.0000	
Ph	borehole	19	6.91	6.7733	7.0833	0.785
	direct tap	34	7.01	6.7700	7.7633	
	stored tap	27	6.87	6.8308	6.9950	
	rain	2	6.87	5.1500	5.1550	
	stream	5	6.95	6.8483	7.7867	
	well	17	6.87	6.7633	7.0933	
Total dissolved solids	borehole	19	16.33	9.4	17.7667	0.203
	direct tap	34	16.33	11.0000	17.7667	
	stored tap	27	17.65	16.3833	21.0917	
	rain	2	17.27	12.8500	13.0500	
	stream	5	16.23	10.8300	134.5850	

	well	17	17.23	16.4500	18.3667	
Magnesium	borehole	19	20.02	18.056	25.4385	0.001
	direct tap	34	26.25	20.1334	74.2572	
	stored tap	27	24.94	18.6537	27.1128	
	rain	2	17.34	11.5950	14.4257	
	stream	5	2.58	0.6326	4.9804	
	well	17	25.35	19.1451	82.0785	
Fluoride	borehole	19	1.03	0	1.9326	0.387
	direct tap	34	0.54	0.0000	2.3116	
	stored tap	27	0.83	0.0000	2.4329	
	rain	2	0.55	0.0600	0.7705	
	stream	5	4.84	2.3347	6.3326	
	well	17	0.44	0.0000	2.3747	

p-value compares median of each physicochemical property per the water source; pH= power of Hydrogen

The physicochemical properties of 104 samples were analysed with 53 and 51 samples collected during the dry and rainy seasons respectively. The results of this study, obtained using the Kruskal-Wallis test, indicate that the average concentrations of ammonia and phosphate were significantly higher during the dry season compared to the rainy season (Table 7).

Table 7: Seasonal variation in physicochemical parameters of water samples.

Physicochemical properties	**Season**	**Number of samples**	**Median**	**Interquartile range**		**P-value**
				25th	**75th**	
Ammonia	Rainy	51	36.24	17.6508	93.2222	0.035
	Dry	53	81.6	21.9524	131.079	
Sulphate	Rainy	51	0.05	0.0185	0.1354	0.747
	Dry	53	0.05	0.0116	0.1354	
Phosphate	Rainy	51	11.38	2.5388	18.0769	0.041
	Dry	53	17.36	1.3831	29.241	
Nitrate	Rainy	51	0.56	0.4964	0.6903	0.637
	Dry	53	0.53	0.477	0.704	
Calcium hardness	Rainy	51	16.31	13.3466	20.7614	0.513
	Dry	53	16.28	11.6222	20.7614	
Total hardness	Rainy	51	118.4	92.5	125.8	0.131
	Dry	53	122.1	109.15	249.05	
Alkalinity	Rainy	51	41	33	45	0.143
	Dry	53	42	37	46.5	
pH	Rainy	51	6.87	6.77	7.1033	0.83
	Dry	53	6.9	6.7817	7.01	
Total dissolved solids	Rainy	51	17.23	16.2333	18.3667	0.116
	Dry	53	16.4	12.1333	17.9167	
Magnesium	Rainy	51	21.2	17.7928	27.6865	0.144
	Dry	53	25.44	19.5054	57.0854	
Fluoride	Rainy	51	0.61	0	2.2274	0.495
	Dry	53	0.73	0	3.0065	

p-value = Median physicochemical parameter during rainy season vrs median during dry season; pH= power of Hydrogen

DISCUSSION

The elevated levels of ammonia, phosphate, and fluoride in some water sources, as well as the high proportion of moderately hard to very hard water samples, highlight the need for effective water treatment and management strategies. The presence of ammonia and phosphate at concentrations exceeding WHO guidelines is a significant concern, as these nutrients can promote the growth of harmful algae and bacteria in water sources (Sharma *et al.*, 2017). Algal blooms can produce toxins that pose risks to human health and aquatic life, while also causing taste and odour problems in drinking water (Backer, 2002; Paerl & Otten, 2013). Phosphate, in particular, is a limiting nutrient in many aquatic systems, and its excessive input can lead to eutrophication and the depletion of dissolved oxygen, with detrimental effects on water quality and ecosystem health (Smith & Schindler, 2009).

While this study focused on physicochemical parameters, the elevated levels of certain contaminants may have unique implications for public health in the Volta Region. The high ammonia concentrations observed far exceed typical environmental levels and could potentially lead to the formation of toxic chloramines if the water undergoes chlorination treatment (Li *et al.*, 2017). Chronic exposure to chloramines has been associated with increased risk of bladder cancer and respiratory issues (Wang *et al.*, 2019). Additionally, the synergistic effects of high ammonia and phosphate levels may create favourable conditions for harmful algal blooms, which can produce cyanotoxins. Recent research has linked cyanotoxin exposure to neurodegenerative diseases like amyotrophic lateral sclerosis (ALS) and Parkinson's disease (Sini *et al.*, 2021). Given the region's reliance on surface water sources, this presents an alarming public health risk that warrants further investigation.

The strong positive correlation between ammonia and phosphate levels in the water samples (Table 5) suggests a common source or related underlying process contributing to their presence. Agricultural runoff, sewage discharge, and industrial effluents are known to be major sources of these nutrients in water bodies (Bhardwaj *et al.*, 2018; Chen *et al.*, 2020). The high levels of ammonia and phosphate in the water samples could be indicative of inadequate wastewater treatment, poor agricultural practices, or unregulated industrial activities in the region. Addressing these sources of pollution through improved waste management, agricultural best practices, and stricter regulations on industrial discharges is crucial for protecting water quality and public health (Ivar do Sul & Costa, 2014; Sasakova *et al.*, 2018).

The presence of acidic water in some sources, as indicated by low pH values, is another area of concern. Acidic water can lead to the corrosion of pipes and the leaching of heavy metals, such as lead and copper, into the water supply (Edzwald, 2011). Exposure to these metals can have serious health consequences, particularly for children, who are more vulnerable to the neurotoxic effects of lead (Edwards, 2014; Wani et al., 2015). Regular monitoring of pH levels and the implementation of appropriate treatment methods, such as pH adjustment and corrosion control, are essential for maintaining the safety and quality of drinking water(Schock & Lytle, 2011).

The high proportion of water samples classified as moderately hard to very hard (Table 2) emphasizes the need for consumer awareness and appropriate water treatment methods. While hard water is not directly harmful to human health, it can cause aesthetic and practical issues, such as taste and odour problems, scaling in pipes and appliances, and reduced soap and detergent efficiency (Dietrich, 2006; Sengupta, 2013). Water softening techniques, such as ion exchange or reverse osmosis, can be employed to mitigate the effects of water hardness and improve the usability of water for various purposes (Djuikom *et al.*, 2011; Wang *et al.*, 2019).

The elevated fluoride concentrations in a substantial proportion of the water samples (Table 3) highlight the importance of regular monitoring and management of fluoride levels in drinking water sources. While fluoride at optimal levels (0.5-1.0 mg/L) can help prevent dental caries, excessive exposure can lead to dental and skeletal fluorosis, a condition characterized by the mottling of teeth and the weakening of bones (Kumar & Sharma, 2011; WHO, 2017). In areas with high natural fluoride occurrence, appropriate defluoridation technologies, such as adsorption, precipitation, or membrane processes, should be implemented to ensure safe drinking water supply (Ali *et al.,* 2016; Ayoob & Gupta, 2006). The elevated fluoride levels found in water samples present a unique challenge in the Volta Region. While dental fluorosis is a well-known consequence of excess fluoride intake, recent studies have highlighted more subtle neurological effects. A meta-analysis by Duan *et al.,* (2018) found that chronic exposure to high fluoride levels was associated with lower IQ scores in children, with effects observed at concentrations similar to those found in this study. Furthermore, emerging research suggests that fluoride may act as an endocrine disruptor, potentially affecting thyroid function and reproductive health (Waugh *et al.,* 2016).

The seasonal variations observed in the physicochemical properties of the water samples (Table 6), with higher median values for ammonia and phosphate during the dry season, suggest that water sources may be more vulnerable to contamination during this period. Reduced water flow, increased evaporation, and concentrated pollutant loads from various sources, such as agricultural runoff, sewage discharge, and industrial effluents, can contribute to the deterioration of water quality during the dry season (Cobbina *et al.,* 2012; Gyamfi *et al.,* 2019). These findings emphasize the need for regular monitoring and adaptive management strategies to ensure the safety and reliability of drinking water supplies throughout the year (Giri & Qiu, 2016). The seasonal variations in water quality observed in this study may have important implications for waterborne disease transmission in the region. The higher levels of ammonia and phosphate during the dry season could create favourable conditions for bacterial growth, including potential pathogens. Research has shown that changes in water chemistry can influence the virulence and antibiotic resistance of waterborne bacteria (Colwell *et al.,* 2003). This suggests that the seasonal fluctuations in water quality may not only affect the abundance of pathogens but also their potential to cause disease.

The higher average levels of total hardness, ammonia, phosphates, and fluoride in tap water samples compared to other sources indicate that the water distribution system may play a role in the elevated levels of these parameters. Aging infrastructure, inadequate treatment processes, and intermittent water supply can contribute to the deterioration of water quality in distribution networks (Lee & Schwab, 2005; Wright *et al.,* 2004). Biofilm formation, leakage, and cross-contamination within distribution systems can also introduce contaminants and compromise the safety of drinking water (Liu *et al.,* 2018). Regular monitoring, maintenance, and upgrades of water distribution infrastructure are essential for ensuring the delivery of safe and high-quality drinking water to consumers (Hrudey *et al.,* 2006).

CONCLUSION

The elevated levels of ammonia, phosphate, and fluoride in some water sources, as well as the high proportion of moderately hard to very hard water samples, highlight the need for effective water treatment and management strategies. The seasonal variations and differences among water sources emphasizes the importance of regular monitoring and targeted interventions to ensure access to safe drinking water. The strong correlations observed between certain physicochemical parameters, such as ammonia and phosphate, suggest the need for a holistic approach to water quality management that considers the interconnectedness of various contaminants and their sources.

The results also highlight the importance of regular monitoring and maintenance of water distribution systems to ensure the delivery of safe and high-quality drinking water to consumers. Water service providers and public health authorities should prioritize the upgrading of aging infrastructure, the optimization of treatment processes, and the implementation of effective disinfection strategies to maintain water quality throughout the distribution network. Based on the seasonal dynamics of water quality observed in this study, there is a need for adaptive management strategies and public awareness campaigns to minimize the risks associated with contaminated water sources, particularly during the dry season.

Overall, this study contributes to a better understanding of the physicochemical properties of water sources in the Volta Region of Ghana and their potential impacts on public health. The findings serve as a basis for future research and inform evidence-based decision-making in water quality management and public health interventions. By addressing the identified water quality issues and promoting access to safe drinking water, we can make significant strides towards improving public health and achieving the United Nations' Sustainable Development Goal 6, which aims to ensure availability and sustainable management of water and sanitation for all.

Recommendations:

Based on the findings of this study, the following recommendations are proposed:

- Implement regular water quality monitoring and prioritize interventions to reduce contamination, particularly for tap water sources. Strengthen monitoring programs, improve wastewater treatment, agricultural practices, and industrial effluent control, and invest in upgrading and maintaining water distribution infrastructure.
- Promote the use of appropriate household water treatment methods like ion exchange or reverse osmosis to address water hardness and fluoride issues. Develop public awareness campaigns and educational programs to inform consumers about the benefits and availability of treatment options, and to minimize risks from contaminated water sources, especially during the dry season.
- Foster collaboration and an integrated approach to sustainably monitor and manage water quality for public health. Strengthen cooperation between water resource managers, public health officials, and local communities, integrate water quality monitoring into public health surveillance systems, and promote a One Health approach recognizing the interconnectedness of human, animal and environmental health.

Declarations:

Ethical Approval: This study forms part of a larger study that received ethical clearance from the Committee on Human Research, Publications and Ethics of Kwame Nkrumah University of Science and Technology (KNUST)- Ghana, with reference number (CHRPE/AP/371/20).

Conflict of interests: The authors declare no conflicts of interest.

Authors Contributions: Emmanuel U. Osisiogu, Kwabena O. Duedu, Bhavana Singh and Patrick K. Feglo developed the concept and directed the research. Emmanuel U. Osisiogu and Samuel N. Boateng carried out sample collection, laboratory and data analysis as well as manuscript draft preparation. All authors have read, reviewed, and approved the content of the last version of this manuscript.

Funding: This study received no external funding.

Availability of Data and Materials: The data presented in this study are available on request from the corresponding author.

Acknowledgements: We would like to express our deepest gratitude to Ms. Priscilla Essandoh, Miss Enyonam Monia Honyo, Miss Sena Adegbedzi, Mr Cyril Kumah, Candy Efe Sepenoo and Ms. Amanda Eyram Banini for their invaluable assistance and support in the laboratory. Their dedication and hard work in assisting in the performance of these extensive experimental procedures and analyses were instrumental to the success of this research. We sincerely thank Dr. Jones Gyamfi and Dr. Gameli Deku for generously providing technical expertise and guidance throughout this research. Your wisdom and insights greatly facilitated the progression of the study.

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