

Research article

Physico-Chemical and Bacteriological Characterization of Groundwater from Banana Plantations in the Agnéby-Tiassa and Sud Comoé Regions of Côte d'Ivoire

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Abstract

In industrial plantations, groundwater is used as a source of drinking water, although it can be affected by contamination from agricultural activities. The aim of our study was to assess the physico-chemical and bacteriological quality of groundwater from industrial plantations in the south of Côte d'Ivoire. The methodological approach consisted of an annual sampling campaign of water supply sources in four (04) plantations from 2016 to 2019 and the analytical approach consisted of determining the various physico-chemical and bacteriological parameters of these different water sources. The physico-chemical analysis used electrochemical and spectrophotometric methods, while the bacteriological analysis was based on the membrane filtration technology. The results showed that the water was characterized by: an average acid pH of 6.09, low mineralization (from 12.83 to 139.29 $\mu\text{S}/\text{cm}$), high iron values ranging from 0.5 to 3.2 mg/L (in 37% of the samples), organic matter ranging from 7.8 to 13.5 mg/L (30% of the samples), and aluminium and ammonium values of 0.3 to 1.1 mg/L and 1.75 to 6.75 mg/L respectively (26% of the samples). Contamination by germs indicative of faecal pollution was also observed in 30% of samples. In conclusion, these waters are of unsatisfactory quality and unfit for consumption. Measures to improve water quality in these plantations should be considered.

Keywords

Groundwater, Physico-chemical Parameters, Bacteriological Parameters, Plantations

1. Introduction

The growing needs associated with demographic growth, rapid urbanisation and the development of economic activities, particularly agriculture and industry, are leading to intense

exploitation of renewable and non-renewable surface water and groundwater throughout the world [1]. Agriculture remains the most water-intensive sector, accounting for 70% of

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Received: 31 January 2025; Accepted: 18 February 2025; Published: 14 March 2025



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demand. This high rate of water demand in this sector means that it contributes to 93% of overall consumption, mainly in developing countries.

The use of rainwater and surface water, as well as withdrawals from underground resources by agricultural practitioners, is leading to the depletion of these water resources, [2] which in turn will make groundwater vulnerable to pollution [3].

These surface groundwater bodies are often affected by diffuse contamination, primarily bacterial pollution of faecal origin, followed by pollution caused by agricultural practices, particularly nitrates and pesticides, or localised pollution of industrial or accidental origin [4]. Once contaminated, these resources are unfit for consumption. According to the WHO, at least 2 billion people in the world use drinking water sources contaminated by faecal matter and 4.2 billion are deprived of adequate sanitation [5]. In Burkina Faso, the growing number of farmers is making a major contribution to the threat to water resources, leading to their deterioration as a result of human activities [6]. In Côte d'Ivoire, the quality of water resources is threatened by the excessive use of phytosanitary products in agriculture. Poor sanitation and inadequate management of solid and liquid waste are also leading to chemical and microbiological pollution of water resources [7]. This pollution has also been highlighted in numerous studies carried out in the south, centre and west of Côte d'Ivoire, both in surface water and groundwater [8].

Given the many sources of contamination of these water resources listed above, it is important to monitor the quality of the water consumed by people in Africa, and particularly in Côte d'Ivoire, in order to contribute to their health safety. It is in this context that the present study set out to assess the physico-chemical and bacteriological quality of groundwater in banana plantations located in Agboville, Azaguié and Motobé

is a very wet area with inter-annual rainfall in excess of 1.500 mm [10].

2.1.2. Type and Period of Study

This was a descriptive cross-sectional study conducted from 2016 to 2019 in two administrative regions in the south of Côte d'Ivoire (Agnéby-Tiassa and Sud Comoé).

2.1.3. Sampling

Water was sampled from seven (07) boreholes on different plantations in three localities (Agboville, Azaguié and Motobé). Samples were taken in 1000 mL polyethylene bottles for physico-chemical parameters and 500 mL for bacteriological parameters. Samples for 2016 were taken during the dry season, i.e. in July, and for the other years, 2017 to 2019, samples were taken during the rainy season, in June, March and May respectively.

2.1.4. Equipment

The equipment consisted of a Palintest® 7100 SE photometer (Great Britain), a pH meter (HACH HQ 11d France), a conductivity meter (HACH HQ 14 d France), a turbidity meter used for physico-chemical parameters, a membrane filtration device for bacterial count and a cellulose ester membrane filter (pore size 0.025µm and 25mm diameter in 100 pack) manufactured by HACH (France) for bacterial enumeration.

2.1.5. Reagents

The reagents used were of analytical quality. The reagents used to measure chemical parameters were Palintest® (Great Britain). Those used for microbiology were: Rapid E coli 2® Agar culture medium, Bile Esculin Agar (BEA) medium and Tryptone Sulfite Neomycin Agar (TSN), all BIO-RAD France brands.

2. Materials and Methods

2.1. Materials

2.1.1. Presentation of the Study Area

The Agnéby-Tiassa region, with the town of Agboville as its regional capital, and the southern Comoé region, with the town of Aboisso as its regional capital. This study concerned the boreholes of four (04) industrial banana plantations belonging to the EGLIN company located along the railway line at Agboville, Azaguié and in the lagoon valleys at Motobé, 25 km from the town of Grand Bassam, on the banks of the Comoé River [9]. The study area extended between 3° and 6° west longitude and 5° and 8° north latitude. The study site, located in a humid tropical climate zone, is characterized by a highly contrasting rainfall and thermal regime. The rainfall regime comprises four seasons: two (02) rainy seasons (March to June and September to November) and two (02) dry seasons (July to August and December to February) [8]. This

2.2. Methods

2.2.1. Collection, Transport and Storage of Samples

The water samples were stored and transported in a cool box at a temperature maintained between 4 and 8°C using cold accumulators in order to respect the cold chain. Samples were taken in accordance with the recommendations of the French National Organization for Standardization (AFNOR) FD T9-520 of 5 October 2005.

2.2.2. Physicochemical Analysis

pH and temperature were determined using a HACH digital pH meter. Turbidity was measured using a HACH nephelometer. Conductivity was measured using a HACH [11]. Organic matter was measured by titrimetry using the AFNOR method. The mineral salts tested were nitrite, nitrate, fluoride, iron, manganese, total alkalimetric strength (TAS), total hy-

drotimetric degree (THD), ammonium, sodium, magnesium, calcium, sulphate, potassium, bicarbonate, zinc, etc. They were detected colorimetrically using a Palintest® 7100 SE photometer with wavelengths ranging from 410 nm to 640 nm. The colour was read using the same colorimetric method.

2.2.3. Bacteriological Analysis

The bacteriological analyses were designed to identify and enumerate total coliforms (TC), *Escherichia coli* (*E. coli*), *Enterococcus faecalis* (*E. faecalis*), *Pseudomonas aeruginosa* (*P. aeruginosa*) and sulphite-reducing anaerobes (SRSA). The technique used to determine these different germs was the membrane filter technique. This involved filtering 100 mL aliquots through a 0.45 µm diameter membrane filter and then placing them on selective culture media at 37°C for 24 hours. The culture media used were: Rapid'E coli 2® Agar for the identification of *E. coli* and total coliforms, TSN agar for the isolation of RSA, pseudosalt or ketrinide medium for the isolation of *Pseudomonas* and BEA agar used for the isolation and enumeration of enterococci by the conventional Petri dish counting method.

2.2.4. Data Processing

A water sample is declared non-drinkable when it contains

at least one non-compliant parameter. A descriptive statistical analysis (averages, medians, minimum, maximum and standard deviation) and a multivariate statistical analysis called Principal Component Analysis (PCA) were used to process the results of the parameters measured on the bore-hole water. Statistica 7.1 software was used to perform PCA on the various water samples, which revealed the factorial designs and total variances.

3. Results

3.1. Analysis of Physico-chemical and Bacteriological Parameters of Groundwater in 2016

The results of the physico-chemical and bacteriological analyses carried out in 2016 are shown in Table 1. The results showed that the water analyzed was very poorly mineralized (an average conductivity of 12.83 ± 64.22 µS/cm with an average pH of less than 6.5. Average levels of iron, colour, turbidity, ammonium, fluoride, aluminium and organic matter exceed the WHO standard (2017). No faecal contamination germs were found in the boreholes.

Table 1. Results of physico-chemical and bacteriological analyses of groundwater in 2016.

Parameters	Min	Average ± Standard deviation	Max	WHO standards (2017)
Physico-chemical parameters				
**Colour (UCV)	15	2.66 ± 10.33	35	< 15
**Turbidity (NTU)	0.09	5.62 ± 12.16	30.4	< 5
Conductivity (µS/cm)	8.6	12.83 ± 64.22	15.6	< 1000
Temperature (C°)	26.4	26.5 ± 0.08	26.5	-
**pH	4.2	5.6 ± 1.23	6.4	6.5 à 8.5
TAS (mg/L)	-	-	-	-
Chlorides (mg/L)	30	87.5 ± 46.0	150	< 250
THD (mg/L)	40	81.12 ± 49.30	140	-
Nitrates (mg/L)	0.01	0.03 ± 0.04	0.09	< 50
Nitrites (mg/L)	0.01	0.01 ± 0	0.01	< 1
**Ammonium (mg/L)	0.04	2.7 ± 3.05	6.72	< 1.5
**Fluorides (mg/L)	0.01	8.33 ± 21.25	48	< 1.5
Manganese (mg/L)	0.007	0.02 ± 0.02	0.02	< 1
**Aluminium (mg/L)	0.22	0.56 ± 0.33	1.14	< 0.2
Iron total (mg/L)	0.01	0.05 ± 0.02	0.06	< 0.3
**Organic matters (mg/L)	3.3	9.6 ± 6.68	21	< 5
Bacteriological parameters				

Parameters	Min	Average \pm Standard deviation	Max	WHO standards (2017)
**TC (UFC/100 mL)	0	0 ± 0	0	0
** <i>E. coli</i> (UFC/100 mL)	0	0 ± 0	0	0
** <i>E. faecalis</i> (UFC/100 mL)	0	0 ± 0	0	0
**ASR (UFC/100 mL)	0	0 ± 0	0	0
<i>P. aeruginosa</i> (UFC/100 mL)	0	0 ± 0	0	0

** : Parameters not in compliance with the WHO Standard (2017)

3.2. Physico.chemical and Bacteriological Parameters of Borehole Water Drilled in 2017

The results of the physico-chemical and bacteriological analyses of the seven (07) borehole waters carried out in 2017 are shown in Table 2. Unlike in 2016, fluoride and ammonium levels complied with the WHO standard (2017). Conductivity

in 2017 was between 100 and 200, compared with less than 100 in 2016. This water has a low mineral content (average conductivity of $139.29 \pm 64.22 \mu\text{S/cm}$). The pH in 2016 was similar to that in 2017, with acidic pH values. Similar to 2016, iron, colour, turbidity, aluminium and organic matter had average values above the standards, with bacteriological contamination different from 2016. En occurrence, une contamination des TC, *E. Coli* et *E. faecalis*.

Table 2. Results of physico-chemical and bacteriological analyses of borehole water obtained in 2017.

Parameters	Min	Average \pm Standard deviation	Max	WHO standards (2017)
Physico-chemical parameters				
**Colour (UCV)	15	34.14 ± 26.12	70	< 15
**Turbidity (NTU)	0.33	35.10 ± 67.68	182	< 5
Conductivity ($\mu\text{S/cm}$)	67.45	139.29 ± 64.22	259	< 1000
Temperature ($^{\circ}\text{C}$)	26.4	27.11 ± 0.51	27.8	-
**pH	5.8	6.4 ± 0.43	7	6.5 à 8.5
TAS (mg/L)	40	147.14 ± 62.37	245	-
Chlorides (mg/L)	2.7	14.8 ± 10.65	32	< 250
THD (mg/L)	5	103.57 ± 113.42	310	-
Nitrates (mg/L)	0.38	1.76 ± 1.31	3.9	< 50
Nitrites (mg/L)	0	0.078 ± 0.13	0.37	< 1
Ammonium (mg/L)	0.01	0.108 ± 0.17	0.43	< 1.5
Fluorides (mg/L)	0.01	0.204 ± 0.01	0.57	< 1.5
Manganese (mg/L)	0.005	0.037 ± 0.02	0.065	< 1
**Aluminium (mg/L)	0	0.07 ± 0.08	0.24	< 0.2
**Iron total (mg/L)	0.05	0.97 ± 1.23	3.2	< 0.3
**Organic matters (mg/L)	2.3	5.5 ± 1.26	12	< 5
Bacteriological parameters				
**TC (UFC/100 mL)	0	4.71 ± 3.4	10	0
** <i>E. coli</i> (UFC/100 mL)	0	0.42 ± 1.13	3	0

Parameters	Min	Average \pm Standard deviation	Max	WHO standards (2017)
** <i>E. faecalis</i> (UFC/100 mL)	0	0.14 \pm 0.38	1	0
**ASR (UFC/100 mL)	0	0.14	1	0
** <i>P. aeruginosa</i> (UFC/100 mL)	0	0 \pm 0	0	0

**: Parameters not in compliance with the WHO Standard (2017)

3.3. Physico.chemical and Bacteriological Parameters of Borehole Water in 2018

The results are similar to those for 2016, and different from those for 2017. The average results for conductivity, pH, colour, turbidity and total iron were similar. Unlike in 2017, no faecal contamination germs were found in any of the boreholes.

Table 3. Results of physico-chemical and bacteriological analyses of groundwater in 2018.

Parameters	Min	Average \pm Standard deviation	Max	WHO standards (2017)
Physico-chemical parameters				
**Colour (UCV)	10	17.86 \pm 10.74	40	< 15
**Turbidity (NTU)	0.15	8.2 \pm 11.47	30.3	< 5
Conductivity (μ S/cm)	63.75	105.11 \pm 30.52	154.5	< 1000
Temperature (C°)	26.1	27.11 \pm 0.56	27.8	-
**pH	5.7	6.2 \pm 0.41	6.9	6.5 à 8.5
TAS (mg/L)	5	132.86 \pm 83.85	235	-
Chlorides (mg/L)	3.1	13.48 \pm 13.74	42	< 250
THD (mg/L)	5	33.57 \pm 20.35	60	-
Nitrates (mg/L)	0.14	0.67 \pm 0.39	1.3	< 50
Nitrites (mg/L)	0	0.028 \pm 0.05	0.14	< 1
**Ammonium (mg/L)	0.01	0.26 \pm 0.66	1.75	< 1.5
Fluorides (mg/L)	0.01	0.24 \pm 0.01	0.75	< 1.5
Manganese (mg/L)	0	0.07 \pm 0.14	0.4	< 1
Aluminium (mg/L)	0.01	0.045 \pm 0.055	0.14	< 0.2
**Iron total (mg/L)	0.01	0.4 \pm 0.7	2.1	< 0.3
Organic matters (mg/L)	0.78	1.56 \pm 0.49	2	< 5
Bacteriological parameters				
TC (UFC/100 mL)	0	0 \pm 0	0	0
<i>E. coli</i> (UFC/100 mL)	0	0 \pm 0	0	0
<i>E. faecalis</i> (UFC/100 mL)	0	0 \pm 0	0	0
ASR (UFC/100 mL)	0	0 \pm 0	0	0
<i>P. aeruginosa</i> (UFC/100 mL)	0	0 \pm 0	0	0

**: Parameters not in compliance with the WHO Standard (2017)

3.4. Analysis of Physico.chemical and Bacteriological Parameters of Groundwater in 2019

The results of the physico-chemical and bacteriological analyses carried out in 2019 are presented in Table 4. Three (03) physico-chemical parameters were found to be non-compliant compared with 2016, 2017 and 2018. Conductivity and pH were similar to 2016. Bacteriological contamination due to faecal contamination germs was observed as in 2017.

Table 4. Results of physico-chemical and bacteriological analyses of borehole water in 2019.

Parameters	Min	Average \pm Standard deviation	Max	WHO standards (2017)
Physico-chemical parameters				
**Colour (UCV)	5	52.86 \pm 122.26	330	< 15
Turbidity (NTU)	0.35	1.41 \pm 0.94	2.57	< 5
Conductivity (μ S/cm)	12.5	24.89 \pm 11.54	45.4	< 1000
Temperature (C°)	27.4	28.4 \pm 0.74	29.7	-
**pH	5.5	6.4 \pm 0.56	7	6.5 à 8.5
TAS (mg/L)	45	207.86 \pm 100.07	350	-
Chlorides (mg/L)	3.1	14.81 \pm 65.99	42	< 250
THD (mg/L)	5	54.28 \pm 39.73	120	-
Nitrates (mg/L)	0.1	0.64 \pm 0.66	0.97	< 50
Nitrites (mg/L)	0	0.028 \pm 0.05	0.14	< 1
**Ammonium (mg/L)	0.01	0.61 \pm 1.28	3.5	< 1.5
Fluorides (mg/L)	0.01	0.32 \pm 0.01	0.84	< 1.5
Manganese (mg/L)	0.001	0.055 \pm 0.106	0.3	< 1
Aluminium (mg/L)	0.01	0.05 \pm 0.034	0.09	< 0.2
Iron total (mg/L)	0.3	0.4 \pm 1.64	2.35	< 0.3
Organic matters (mg/L)	0.66	1.56 \pm 1.45	4.63	< 5
Bacteriological parameters				
**TC (UFC/100 mL)	0	2.57 \pm 3.26	7	0
** <i>E. coli</i> (UFC/100 mL)	0	2.57 \pm 3.26	7	0
** <i>E. faecalis</i> (UFC/100 mL)	0	25.14 \pm 59.76	160	0
ASR (UFC/100 mL)	0	0 \pm 0	0	0
<i>P. aeruginosa</i> (UFC/100 mL)	0	0 \pm 0	0	0

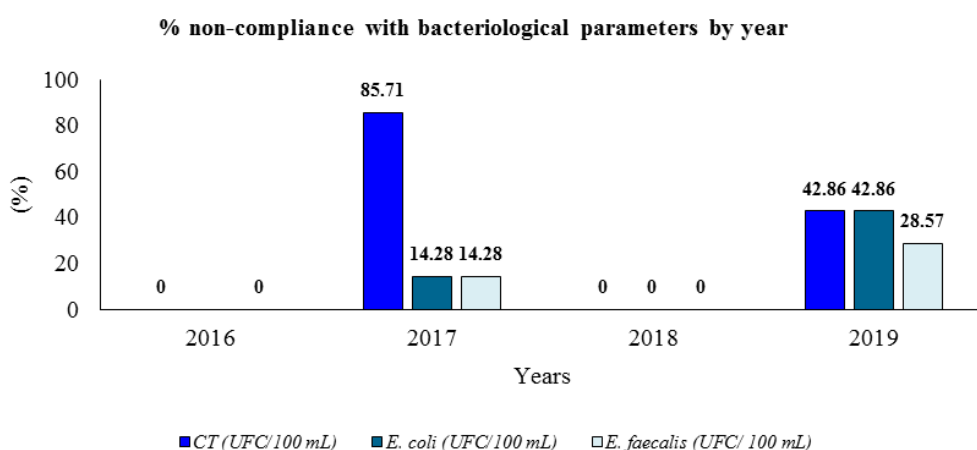
** : Parameters not in compliance with the WHO Standard (2017)

3.5. Percentage of Non.compliance for Physico.chemical and Bacteriological Parameters by Year

In terms of physico-chemical analysis, parameters such as colour, turbidity, pH, iron, organic matter, aluminium, ammonium and fluoride were non-compliant. Colour and pH remained non-compliant over the four years of the study (Table 5). Non-compliances were observed in 2017 and 2019 for TC, *E. coli* and *Enterococcus faecalis* (Figure 1).

Table 5. Percentage of physico-chemical parameters that do not comply with WHO standards (2017).

% non-compliance of physico-chemical parameters by year					
Parameters	2016	2017	2018	2019	Average
Colour (UCV)	33.33	42.86	42.86	14.28	33.33
Turbidity (NTU)	16.66	42.86	42.86	0	25.60
pH	100	42.86	71.43	42.86	64.29
Ammonium (mg/L)	33.33	0	14.28	14.28	15.47
Fluorides (mg/L)	16.66	42.86	0	0	14.88
Aluminium (mg/L)	100	14.28	0	0	28.57
Iron total (mg/L)	0	42.86	28.57	71.43	35.72
Organic matters (mg/L)	66.66	28.57	0	0	23.81

**Figure 1.** Bacteriological parameters not in compliance with WHO standards (2017).

3.6. Water Classification Using Principal Component Analysis

Principal component analysis was performed on the physico-chemical and bacteriological parameters (Figures 2 and 3). Projection of the variable contents onto the factorial plane (1×2) shows that 39.82% of the total variance is expressed (Figure 2). The F1 axis represents 23.09% of the total variance. At the positive pole are the full alkalimetric titre, chlorides, conductivity, iron and nitrates. At the negative pole were organic matter, aluminium and ammonium. This axis represents low mineralization and pollution based on inorganic nitrogenous matter, reflecting chemical pollution of the borehole water in the study area. Axis F2 accounts for 12.59% of the total variance. Its positive part includes the total hydrotimetric degree (THD), turbidity and nitrites. At the nega-

tive pole are manganese, *Escherichia coli* and *Enterococcus faecalis*. This axis highlights faecal pollution with high turbidity. The hierarchical classification of boreholes on the basis of the physico-chemical and bacteriological quality of the water enabled us to distinguish three groups (Figure 3).

1. Group 1, which contains borehole F1 and includes parameters such as nitrite, turbidity, DHT, colour, TC and chloride.
2. Group 2 includes the F1 borehole and the Station 21 borehole. Borehole F1 contains the temperature and borehole station 21 the *Enterococcus faecalis*, *Escherichia coli* and manganese variables.
3. Group 3, made up of all the other boreholes, characterized by a positive coordinate on the axis, contains the variables organic matter, aluminium, ammonium, fluorides, TC, pH, chlorides, iron, TAC and nitrates.

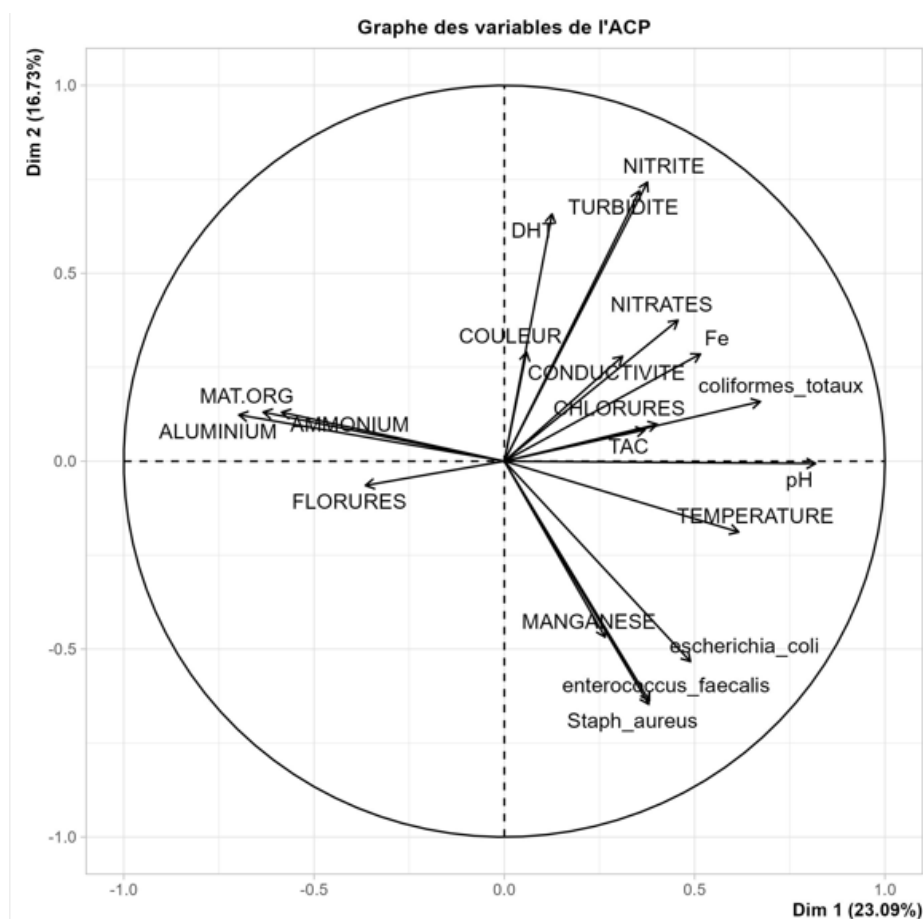


Figure 2. Projection on the factorial plane (1 x 2) of physico-chemical and bacteriological parameters.

4. Discussion

Groundwater is one of the main sources of drinking water for the population. This study will assess the physico-chemical and bacteriological quality of groundwater consumed in industrial plantations.

4.1. Physico.chemical Analysis

From 2016 to 2019, physical parameters such as pH and turbidity exceeded the admissible criteria of the standard (WHO 2017), which was 6.5 to 8.5 for pH. The average pH of the water analyzed from 2016 to 2019 was 5.6, 6.4, 6.2 and 6.4 respectively. Borehole water from these banana plantations is therefore acidic. However, the acidity of the water is more pronounced in dry periods (5.6 in 2016) than in rainy periods (6.4, 6.2 and 6.4 in 2017, 2018 and 2019). The acidification of these waters could result from the decomposition of plant organic matter, with the production of CO_2 in the first layers of the soil. The presence of CO_2 in the water could facilitate the hydrolysis of silicate minerals and the formation of HCO_3^- ions [12].

This acidity is consistent with water found in basement aquifers in Côte d'Ivoire. This aspect of basement groundwater has been reported in several studies. These pH values

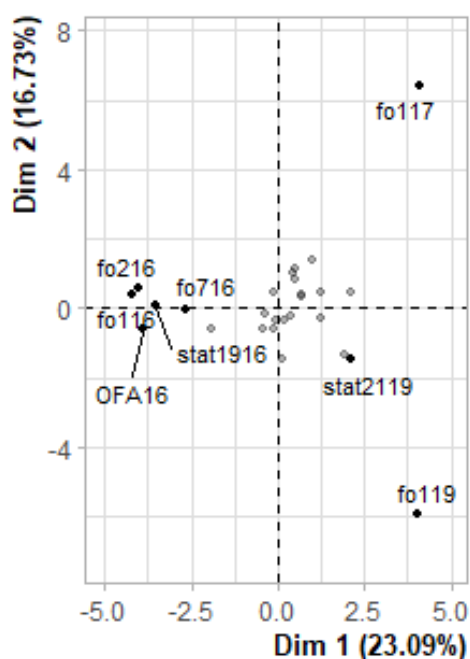


Figure 3. Projection on the factorial plane (1 x 2) of the boreholes.

are also in line with those of [13] and [10] at Agboville.

The turbidity standard set by the WHO is 4 NTU (WHO, 2017). The water samples analyzed from 2016 to 2018 have turbidities of 5.62 NTU, 35.10 NTU and 8.2 NTU respectively. Turbidity is higher in the rainy season than in the dry season. These turbidities are thought to be due to the presence of matter such as clay, silt, fine organic and inorganic matter and plankton. In general, water with high turbidity has an unpleasant appearance, colour, taste and odour due to the presence of suspended matter and colloidal matter. In addition, water with high turbidity can cause gastrointestinal illness due to the attachment of micro-organisms to particles suspended in the water. The temperature of the water analyzed was respectively 26.5°C, 27.11°C, 27.11°C, and 28.4°C higher than 25°C. The temperature appears higher in the dry season (26.5°C in 2016) and (27.11°C, 27.11°C and 28.4°C) in the rainy season in 2017, 2018 and 2019 respectively. Water temperature could influence all the physical and chemical reactions in water. It could play a major role in the dissociation of salts and chemical equilibria [14].

Analysis of the minerals revealed that parameters such as chlorides, nitrates, nitrites and manganese remained compliant over the four years of study. However, the analysis revealed high concentrations of fluoride, aluminium and iron. The standards set by the WHO are 1.5 mg/L for fluoride, 0.2 mg/L for aluminium and 0.3 mg/L for iron. The maximum fluoride concentrations were 48 mg/L in 2016 and 1.14 and 0.24 mg/L for aluminium in 2017 and 2018. Average iron concentrations were 0.97 mg/L and 0.4 mg/L in 2017 and 2018 respectively. The high iron values could be explained by the fact that the soils in this region are ferrallitic soils, which are highly leached under abundant rainfall due to the region's typical humid tropical climate. These abnormal concentrations of iron can also be explained by pollution of anthropogenic origin, such as the leaching of agricultural land, domestic waste and sewage [15]. The concentration of iron found in the present study is as high as in that of [16]. This author found high iron concentrations of 3.84 mg/L. Ammonium and organic matter concentrations exceeded WHO threshold values (1.5 mg/L) for ammonium and 5 mg/L for organic matter. The maximum values were 1.75 mg/L in 2018 and 3.5 mg/L in 2019 for ammonium. The maximums were 21 mg/L in 2016 and 12 mg/L in 2017 for organic matter. Ammonium is a component of the nitrogen cycle, and its high concentration could be justified by environmental degradation of water quality due to agricultural activities and wastewater discharges [17]. The presence of ammonium could then result in a process of incomplete degradation of the organic matter in the water. [8]. This hypothesis is confirmed by the work of [18]. According to this author, ammonium comes from the excretion of living organisms, from the reduction of organic nitrogen during the biodegradation of waste, and above all from direct inputs from domestic and agricultural sources.

4.2. Bacteriological Analysis

Analysis of the water revealed the presence of faecal contamination bacteria. Germs such as *E. coli* and *Enterococcus faecalis* showed values in 2017 and 2019 that exceeded the WHO standard of 0 CFU/100 mL. The maximum values achieved for *E. coli* were 3 CFU/100 mL in 2017 and 7 CFU/100 mL in 2019. The maximum values for *Enterococcus faecalis* were 1 CFU/100 mL in 2017 and 160 CFU/100 mL in 2019. The presence of *E. coli* could indicate recent faecal contamination and *Enterococcus faecalis* could indicate old faecal contamination. The presence of faecal contamination germs could be explained by faecal contamination, with the risk of pathogenic germs being present in the water. The presence of these germs could be an indicator of faecal pollution, largely of human origin. These bacteriological parameters demonstrate the influence of human activity on water quality [19].

The faecal origin of the pollution of groundwater resources in the sub-prefectures of Grand-Morié and Azaguié in the department of Agboville has been highlighted by the work of [10].

The presence of faecal contamination germs exposes consumers to the risk of water-borne diseases such as gastro-enteritis, diarrhoea, dysentery according to [20]. Our results are contrary to those of a laboratory that found none of the microorganisms tested in the water from the borehole in the village of Kanphoin in Man. This borehole is equipped with a human-powered pump, so the water was microbiologically potable.

4.3. Analysis of Non-compliances

The average percentages of non-compliance over the four years for physico-chemical parameters were 33% for colour, 26% for turbidity, around 15% for ammonium and fluoride, 63% for pH, 36% for iron and 23% for organic matter (Table 5) [21] also found the same non-compliances in the physico-chemical analysis of groundwater and surface water in five (05) regions of Côte d'Ivoire.

The results of the bacteriological analysis showed the presence of faecal contamination bacteria (TC, *E. coli* and *Enterococcus faecalis*). These results are similar to those of [22], where 26.77% of borehole water was contaminated with TC and 2.03% with faecal streptococci. The quality of the borehole water does not comply with the potability standards set by the WHO in 2017, which stipulate that water intended for consumption should contain no more than 0 CFU/100 mL of germs.

4.4. Principal Component Analysis

The results were statistically analysed using a multivariate analysis method known as principal component analysis (PCA). This method has long been used in hydrochemical

analysis [23] for the simultaneous study of a large number of variables to highlight the relationships between these variables and the phenomena that may explain these relationships. Statistical analysis of the data was carried out on a data matrix of 20 variables and 27 boreholes, i.e. 20 variables and 27 individuals over the four years of the study. Analysis of the factorial design for the physico-chemical and bacteriological variables expressed 39.82% of the total variance. The F1 axis showed low mineralization and pollution of the water in the boreholes studied by inorganic nitrogenous matter. The factor2 axis highlighted faecal pollution with high turbidity correlated with *Escherichia coli*. The variance rates expressed are close to [24] with 39.098% for borehole water in the Man department (Côte d'Ivoire) in the dry season.

The variance rates expressed are low compared with those of [25] of 59.60% for the study of well and borehole water in the upper Korama catchment area, Zinder region, Niger. Pollution by inorganic nitrogenous matter can be explained by the use of ammonium-based fertilisers or pesticides necessary for the upkeep of banana plantations. Bacterial pollution of faecal origin may be due to a lack of sanitation. It should also be noted that we have bacterial pollution due to staphylococcus aureus, which can be explained by the fact that bananas are handled and washed by hand, leading to contamination of the groundwater.

5. Conclusions

The aim of the study was to assess the physico-chemical and bacteriological quality of groundwater consumed in industrial plantations in the south of Côte d'Ivoire. The physico-chemical analyses revealed that the borehole water studied was acidic and poorly mineralized. Non-compliances have been noted over the past four (04) years, mainly in terms of turbidity, iron, organic matter and ammonium, the values of which exceeded WHO standards for drinking water. Bacteriological analysis revealed bacterial pollution of faecal origin in two (02) of the seven (07) boreholes analyzed. The presence of *Staphylococcus aureus* is also a health risk for consumers of this groundwater.

Abbreviations

AFNOR	French National Organization for Standardization
TAS	Total Alkalimetric Strength
THD	Total Hydrotimetric Degree
TC	Total Coliforms
<i>E. coli</i>	<i>Escherichia coli</i>
<i>E. faecalis</i>	<i>Enterococcus faecalis</i>
<i>P. aeruginosa</i>	<i>Pseudomonas aeruginosa</i>
ASR	Anaerobic Sulphite Reducers
PCA	Principal Component Analysis

Acknowledgments

The authors would like to thank the National Public Health Laboratory through its Food Control Laboratory, the National Institute of Public Sanitation and the Department of Analytical Sciences and Public Health, Pharmaceutical and Biological Sciences Training and Research Unit of University Felix Houphouët Boigny, Abidjan, Côte d'Ivoire for carrying out this work.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Harrat N, Achour S. Pollution physico-chimique des eaux de Barrage de la région d'El Tarf. Impact sur la chloration.
- [2] Baechler L. La bonne gestion de l'eau: un enjeu majeur du développement durable. Eur En Form 2012; 3–21.
- [3] Yapo RI, Mambo V, Alder AC, Ohou-Yao MJ, Ligban R, Dao D, et al. Caractérisation saisonnière des eaux de puits à usage maraîchère et domestique de Korhogo (Côte d'Ivoire). Int J Biol Chem Sci 2016; 10: 1433. <https://doi.org/10.4314/ijbcs.v10i3.41>
- [4] de MARSILY G, Besbes M. Les eaux souterraines, Cairn/Softwin; 2017, p. 25–30.
- [5] OMS. (2022) eau potable, <https://www.who.int/fr/news-room/fact-sheets/detail/drinking-water> consulté le 20-05-2023. n.d.
- [6] Kyakimwa Kyalwahi O, Musoki Furaha B, Nyanzereka Mokala S. Évaluation de la qualité bactériologique des eaux de puits de la Commune Mususa en Ville de Butembo 2023. <https://doi.org/10.57988/CRIG-2426>
- [7] MINISTERE DE L'HYDRAULIQUE. Côte d'Ivoire: 2010.
- [8] Ernest AK, Nagnin S, Gbombélé S, Théophile L, Solange OM, Pacôme ZS. Groundwater pollution in Africans biggest towns: case of the town of Abidjan (Côte D'ivoire). Eur J Sci Res.

- [9] Sidoine EB, Brice DKE, Siaka T, Michel KA, Boni N, Kouman K, et al. Etat Phytosanitaire Dans Les Plantations Industrielles De Bananiers Dans La Lutte Contre La Cercosporiose Noire En Côte d'Ivoire. *Eur Sci J ESJ* 2020; 16. <https://doi.org/10.19044/esj.2020.v16n12p393>
- [10] Orou RK, Soro G, Soro DT, Fossou RMN, Onetie OZ, Ahoussi EK, et al. Variation Saisonnière De La Qualité Physico-Chimique Des Eaux Souterraines Des Aquifères d'Altérites Du Département d'Agboville (Sud-Est De La Côte d'Ivoire). *Eur Sci J ESJ* 2016; 12: 213. <https://doi.org/10.19044/esj.2016.v12n17p213>
- [11] Helrich K. Association of Official Analytical Chemists, (1990) Official Methods of Analysis of the Association of Official Analytical Chemists n.d.
- [12] Ahoussi EK, Keumean NK, Kouassi MA, Koffi BY. Etude des caractéristiques hydrogéochimiques et microbiologiques des eaux de consommation de la zone périurbaine de la ville de Man: cas du village de Kpangouin (Côte d'Ivoire). *Int J Biol Chem Sci* 2018; 11: 3018. <https://doi.org/10.4314/ijbcs.v11i6.37>
- [13] Ahoussi K, Oga Y, Koffi Y, Kouassi A, Soro N, Biemi J. Caractérisation hydrogéochimique et microbiologique des ressources en eau du site d'un Centre d'Enfouissement Technique (CET) de Côte d'Ivoire: Cas du CET de Kossihouen dans le District d'Abidjan (Côte d'Ivoire). *Int J Biol Chem Sci* 2012; 5: 2524–42. <https://doi.org/10.4314/ijbcs.v5i6.32>
- [14] Rodier J. Analyse de l'eau. 9ème Edition. Dunod; 2009.
- [15] Gbagbo T, Kpaibe SP, Gokpeya K, Able N, Seki T, Bakayoko A, et al. Caractérisation physicochimique et bactériologique des eaux de consommation de la nappe phréatique du village M'pody (Cote d'Ivoire): Physicochemical and bacteriological characterization of drinking water from the groundwater from M'pody village (Cote d'Ivoire). *J Rech Sci L'Université Lomé* 2020; 22: 775–792.
- [16] Eblin S, Sombo A, Soro G, Aka N, Kambire O, Soro N. Hydrochimie des eaux de surface de la région d'Adiaké (sud-est côtier de la Côte d'Ivoire). *J Appl Biosci* 2014; 75: 6259. <https://doi.org/10.4314/jab.v75i1.10>
- [17] Hadj C. Etude comparative de la qualité physico-chimique et bactériologique entre eau de puits de Si Abdelghani (Taret) et Puits de Daïa (Ghardaïa) 2020.
- [18] Kanohin F, Otchoumou E, Yapou OB, Dibi B, Bonny AC. Caractérisation physico-chimique et bactériologique des eaux souterraines de Bingerville. *Int J Biol Chem Sci* 2018; 11: 2495. <https://doi.org/10.4314/ijbcs.v11i5.43>
- [19] LE MDES, DE SDMC. Caractérisation Hydrogéochimique et Microbiologique des Eaux Souterraines dans le Système d'aquifères Multi Couche de la Région de Pointe-Noire en République du Congo. *Larhyss J*, 2016: 28: 257–273.
- [20] Amadou H, Laouali M, Manzola A. Analyses physico-chimiques et bactériologiques des eaux de trois aquifères de la région de Tillabery: application des méthodes d'analyses statistiques multi variées. *Larhyss J*, 2014.
- [21] Amin CN, Dibi KS, Yapou WT, Able CN, Kpaibé PAS, Kouadio L, et al. Chemical and bacteriological control of drinking water from 15 villages in Côte d'Ivoire. *Int J Nutr Food Sci* 2019; 7: 180–186. <https://doi.org/10.11648/j.ijnfs>
- [22] Soncy K, Djeri B, Anani K, Eklou-Lawson M, Adjrah Y, Karou D, et al. Évaluation de la qualité bactériologique des eaux de puits et de forage à Lomé, Togo. *J Appl Biosci* 2015; 91: 8464. <https://doi.org/10.4314/jab.v91i1.6>
- [23] Mouissi S, Alayat H. Utilisation de l'Analyse en Composantes Principales (ACP) pour la caractérisation Physico-chimique des eaux d'un écosystème aquatique: Cas du Lac Oubéira (Extrême NE Algérien). *J Mater Environ Sci*, 2016; 7: 2214–2220.
- [24] Kernoug S, Slamani F. Etude comparative de la qualité physico-chimique et de la qualité bactériologique de l'eau potable obtenue par deux procédés de traitement des eaux de surface: le cas de la station de Taksebt et la station d'Imssouhal 2022. <https://dspace.ummto.dz/handle/ummto/19841>
- [25] Souleymane IMS, Babaye MSA, Alhassane I, Boureima O. Caractérisations hydrogéochimiques et qualités des eaux de la nappe phréatique du haut bassin versant de la Korama, commune de Droum/région de Zinder (Niger/Afrique de l'Ouest). *Int J Biol Chem Sci* 2020; 14: 1862–1877. <https://doi.org/10.4314/ijbcs.v14i5.29>

Research Field

Carine Nina Ablé Physico-chemical analysis of natural substances (water, food, drinks and drugs, etc.), Dosage of drugs, Research into food contaminants (heavy metals, pesticides, antimicrobial residues and aflatoxins, etc.)

Sawa André Philippe Kpaibe: Physico-chemical analysis of natural substances (water, food, drinks and drugs, etc.), Dosage of drugs, Research into food contaminants (heavy metals, pesticides, antimicrobial residues and aflatoxins, etc.)

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