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Physicochemical, Metallic, and Bacteriological Characterization of Coastal Waters off Bonfi (Conakry, Guinea)

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Abstract

Coastal waters are increasingly exposed to untreated domestic, urban, and industrial discharges, potentially affecting their physicochemical, metallic, and bacteriological quality. This study assessed marine water quality along the Bonfi coastline (Conakry) to identify potential contamination risks. Thirty samples were collected from ten stations (E1 - E10) in triplicate and analyzed for physicochemical parameters, nutrients, four metals (Fe, Cr, Mn, Cu), and three bacteriological indicators using standardized methods. Results were compared with international reference values due to the absence of specific Guinean marine water standards. Turbidity exceeded the European reference value of 5 NTU at one station, while the mean pH was 7.07. Total iron averaged 0.43 ± 0.07 mg/L, exceeding the European reference value of 0.06 mg/L. Sulfates (2297 ± 131 mg/L) and nitrites (1.56 ± 0.37 mg/L) also showed elevated concentrations. Nitrates, phosphates, chromium, manganese, and copper remained within the reference limits. Mean fecal and total coliform concentrations were 40 and 77 CFU/100mL, respectively, while fecal streptococci remained below the European bathing water threshold. Overall, Bonfi coastal waters showed iron-related contamination, elevated mineralization, and nitrite concentrations, but no concerning bacteriological contamination according to the reference criteria used. These findings highlight the need for strengthened coastal water quality monitoring, particularly regarding iron inputs and seasonal bacteriological variations associated with fishing activities.

Keywords

Bonfi Coastline, Conakry, Marine Water Quality, Heavy Metals, Physicochemical Parameters, Bacteriological Contamination, Coastal Management

1. Introduction

Coastal zones are sensitive ecological interfaces subject to continuous inputs of runoff water laden with domestic, urban, and industrial discharges—most of which are untreated prior to their release into the marine environment [1]. These inputs can contribute to the degradation of the quality of receiving waters through the introduction of chemical contaminants—notably certain metallic elements—as well as microorganisms that serve as indicators of fecal contamination, such as fecal coliforms and fecal streptococci. Such contamination poses a potential threat to the quality of the aquatic environment and to the health of populations exposed to these waters [2].

In West Africa, several studies have documented varying levels of metal contamination in coastal waters and sediments, generally associated with the proximity of industrial sites, ports, or landfills—as demonstrated in the Konkouré River estuary in Guinea [1], the Dakar coast in Senegal [3], and the Lagos lagoon complex in Nigeria [4].

Beyond the mere quantification of trace metal elements, a robust characterization of coastal water quality requires an integrated approach combining standard physicochemical parameters (temperature, pH, turbidity, salinity, conductivity), nutrients (nitrates, nitrites, phosphates, sulfates), metal contamination, and fecal bacterial indicators [5]. This multi-parameter approach—presented here as an integrated characterization method—represents a methodological innovation compared to studies limited to a single type of contaminant; it enables the prioritization of the most relevant courses of action for coastal management, rather than simply documenting the existence of contamination. From a bacteriological standpoint, fecal coliforms, total coliforms, and fecal streptococci (including the enterococci subgroup) remain the primary indicators used to assess health risks associated with fecal contamination in surface waters and bathing waters; fecal streptococci are recognized as being more persistent in the environment than coliforms [6]-[8], making them useful complementary indicators for detecting fecal contamination in aquatic environments [9].

In Guinea—specifically along the Bonfi coastline in Conakry, an area subject to increasing urbanization, artisanal fishing, and the proximity of industrial and port facilities—incidents of coastal water pollution have already been reported by local maritime and environmental authorities [10] [11], yet systematic, multi-parameter data on water quality remain scarce in the scientific literature. The aim of this study is to (I) comprehensively characterize the physicochemical, metal (Fe, Cr, Mn, Cu), and bacteriological quality of the marine waters off the Bonfi coast; (II) compare these results with available international standards; and (III) identify concrete courses of action for the monitoring and management of this coastal zone.

2. Materials and Methods

2.1. Presentation of the Study Area

Guinea, located along the West African Atlantic coast, is endowed with significant

fisheries resources. Its coastline extends over approximately 300 km, while its continental shelf covers about 43,000 km^2. The Guinean coastal zone is characterized by an extensive hydrographic network, numerous estuaries and mangrove ecosystems, which contribute to its rich marine biodiversity and fisheries productivity [12].

Beyond the Autonomous Port of Conakry, the port of Bonfi serves as a significant hub for economic and social activity in the country. It is accessible by road via the southern coastal road (south corniche).

In the Matam commune of Conakry, the Bonfi landing site ranks second in the capital—following the port of Boulbinet—in terms of the volume of fish landed. The site has previously undergone development work supported by Japanese cooperation. A variety of artisanal fishing vessels operate at Bonfi, including kourou, gbankenyi, salan, flimbote, and yoli boats. As for fishing gear, the equipment used includes drift gillnets (for Ethmalosa and demersal species), encircling gillnets (for mullet, Ethmalosa, and croaker/otolithids), set gillnets (with small, large, or very large mesh sizes), purse seines, handlines, and longlines.

2.2. Equipment

- Memmert drying oven; - 100 mL graduated tubes;
- HACH-CO 150 conductometer; - 250 mL beaker;
- DR 2000 spectrophotometer; - 1.50 L polyethylene bottles;
- Variomag multipoint magnetic stirrer; - Absorbent disc;
- Thermometer (readable to 0.5˚C); - Glass bottles;
- Colorimetric flask; - Cellulose membrane (0.45 µm);
- COMORT P1500 pH meter; - Markers;
- HACH 2100P turbidimeter; - Petri dish;
- Cooler.

2.3. Study Site and Sampling Strategy

Collecting seawater samples is a highly complex operation that determines the reliability of analytical results and their subsequent interpretation. The collection process varies according to the elements being measured, and the required sample volume depends on the type of analysis to be performed.

Sampling took place on June 29 and 30, 2021 (during the rainy season) at 2:00 PM (low tide).

The samples were collected in 500 mL polyethylene bottles, which had been precleaned and rinsed several times with distilled water. They were then transported in a cooler—within 24 hours of collection—to the CERE laboratory and the Lab'Eaux & Hygiene facility for analysis.

The study was conducted along the Bonfi coastline, located in the Matam commune of Conakry, Republic of Guinea. The sampling design consists of ten stations, numbered E1 through E10, strategically distributed along the coastline to cover various areas potentially affected by urban, domestic, and industrial dis-

charges.

At each station, three independent samples (a, b, and c) were collected, resulting in a total of 30 seawater samples intended for physicochemical and microbiological analyses.

The characterization of these stations also takes into account their geographic location (GPS coordinates: Table 1), tidal conditions at the time of sampling (high tide, low tide, or flood tide), and rainfall conditions (the date and period of sampling, presence or absence of precipitation).

These parameters allow for better interpretation of the spatial and temporal variations in marine water quality.

The selection of the ten stations is based on: proximity to residential areas and domestic discharge points; exposure to industrial and port activities; the presence of fishing and landing operations; the diversity of coastal sectors; and the ability to compare potentially polluted areas with less exposed sectors.

Table 1. Location of sampling points using GPS.

E_n	Latitude Nord (˚)	Longitude Ouest (˚)
E_1	9.549454	013.614982
E_2	9.539659	013.618529
E_3	9.536529	013.634313
E_4	9.520945	013.647969
E_5	9.521645	013.631298
E_6	9.528291	013.616933
E_7	9.543875	013.602745
E_8	9.532838	013.597247
E_9	9.519547	013.609839
E_{10}	9.512376	013.626865

2.4. Measured Parameters and Analytical Methods

Physicochemical parameters—specifically temperature and pH, measured directly in the field, as well as turbidity, salinity, conductivity, and nutrient concentrations (nitrates, nitrites, phosphates, and sulfates)—were determined in the laboratory following standardized water quality analysis protocols [5]. Metallic elements, including total iron, total chromium, manganese, and copper, were also analyzed, primarily using atomic absorption spectrophotometry.

Furthermore, bacteriological indicators—comprising fecal coliforms, total coliforms, and fecal streptococci—were identified and enumerated using the membrane filtration technique. This method involves filtering water samples and subsequently incubating them on selective culture media, in accordance with reference methods [5]. The results obtained were expressed as colony-forming units per 100 milliliters (CFU/100mL).

Analytical Description of Samples and Quality Control Procedures

Marine water quality analysis was conducted using standardized physicochemical and microbiological methods, combining in situ measurements with laboratory analyses. The procedures encompassed sample preparation, preservation, analytical conditions, and quality control measures to ensure the reliability and reproducibility of the results.

1) Measurement of physicochemical parameters

- In situ temperature was determined at the time of sampling using a Hanna Checktemp1 electronic thermometer.

In situ pH was determined using a COMORT P1500 pH meter (a French brand).

- Salinity and electrical conductivity were measured using a HACH CO 150 conductivity meter (an American brand).

- Turbidity was determined using a HACH 2100P turbidimeter and is expressed in nephelometric turbidity units (NTU).

2) Laboratory chemical analyses

Concentrations of nitrates, nitrites, phosphates, and sulfates were determined using a spectrophotometer (HACH DR/2000). Results were expressed in mg/L.

3) Bacteriological analyses

Fecal coliforms, total coliforms, and fecal streptococci were analyzed using the membrane filtration method. An appropriate volume of water (typically 100 mL) was filtered through a sterile 0.45 µm membrane. The membranes were then placed onto selective culture media (m-FC for fecal coliforms, m-Endo for total coliforms, and M-Enterococcus for fecal streptococci) and incubated under conditions specific to each bacterial group (details to be specified). Results were expressed in CFU/100mL.

2.5. Reference Standards Used

In the absence of specific Guinean standards for coastal marine water quality, the results were compared against reference values derived from European regulations on water intended for human consumption (Directive 98/83/EC) [6], World Health Organization (WHO) recommendations for drinking water [13], and—with regard to bacteriological indicators and turbidity—the European Directive on the management of bathing water quality (2006/7/EC) [8], as well as WHO guidelines on the quality of coastal waters for recreational use [13]. The indicative threshold adopted for phosphates (0.4 mg/L) represents an order of magnitude commonly used to signal a risk of eutrophication in coastal waters, although specific criteria vary significantly depending on the geographical area and the governing authorities [14]. This combination of standards—frequently employed in environmental studies in West Africa due to the lack of specific local references for marine waters—is highlighted as a significant methodological limitation in Section 5; indeed, several of these thresholds were designed for fresh water intended for human consumption, rather than for seawater, whose natural ionic composition (particularly regarding sulfates) differs fundamentally from that of

fresh water.

Reference Thresholds for Assessing Marine Water Quality

To assess the quality of water sampled along the coastline of Bonfi in Conakry, it is recommended to compare the analytical results against reference values suitable for coastal marine waters.

However, a distinction must be made among three types of reference criteria:

- Ecological quality of the marine environment: protection of aquatic organisms and maintenance of the ecological balance;
- Sanitary quality of bathing waters: protection of human health against microbiological contamination;
- Chemical quality: prevention of toxic effects related to nutrients and metals.

The thresholds provided below serve as an indicative framework for scientific comparisons.

a) Physicochemical reference thresholds

Marine water quality assessment relies on physicochemical parameters and their reference values. Table 2 presents the selected parameters, their measurement units, and the accepted reference ranges: temperature (25˚C - 32˚C), pH (7.5 - 8.5), turbidity (<5 NTU), salinity (30 - 37 PSU), and conductivity (45,000 - 55,000 µS/cm). These indicators help characterize marine water quality and identify environmental changes that may affect aquatic organisms and coastal ecosystems.

Table 2. Indicative reference values for key physicochemical parameters used to assess marine water quality [14].

Parameters	Indicative values for marine waters	Units	Interpretation
Temperature	25 - 32	˚C	Indicative range—to be compared with local natural conditions
pH	7.5 - 8.5	-	Typical range for slightly alkaline marine water
Turbidity	Less than 5	NTU	Relatively clear water; should be adjusted based on the site's natural turbidity.
Salinity	30 - 37	PSU	Indicative range for coastal marine waters
Conductivity	Approximately 45,000 - 55,000	µS/cm	Reference values for marine water with a salinity close to 35 PSU at a controlled temperature

These ranges do not constitute universal regulatory limits. Temperature, salinity, and conductivity depend on factors such as the season, precipitation, freshwater inputs, and hydrodynamic conditions. pH must also be interpreted in the context of the environment's natural variations. Notably, the EPA uses a range of 6.5 to 8.5 as a reference for the protection of aquatic life in marine waters.

b) Nutrient reference thresholds

Nutrients are particularly important for assessing inputs of domestic and urban pollution, as well as the risks of eutrophication in the marine environment (Table 3).

Table 3. Indicative reference values for key nutrient and mineral parameters used to assess marine water quality [15].

Settings	Indicative reference values	Units
Nitrates (NO_3^-)	≤0.10 mg/L as nitrate nitrogen (NO_3-N)	mg N/L
Nitrites (NO_2^-)	≤0.035 mg/L as nitrite nitrogen (NO_2-N)	mg N/L
Phosphates (PO_4^{3-})	0.001 - 0.010 mg/L as phosphorus (PO_4-P)	mg P/L
Sulfates (SO_4^{2-})	Approximately 2700 mg/L in natural seawater	mg/L

These values serve as benchmarks for comparison rather than universal toxicity thresholds. Australian reference values for coastal waters, for instance, indicate a range of 1 to 10 µg/L for phosphorus in the form of phosphate.

c) Reference thresholds for metallic elements

For metals, it is preferable to prioritize criteria designed for the protection of aquatic organisms in saline environments (Table 4).

Table 4. Indicative reference values for metals in marine waters for the assessment of metal contamination [16].

Metals	Indicative reference	Units	Nature of the criterion
Total iron (Fe)	No universal marine threshold is established	mg/L	Assessment based on the geochemical background
Chromium VI (Cr VI)	0.050	mg/L	Marine chronic criterion
Chromium III (Cr III)	No EPA marine criterion has been established.	mg/L	Specific assessment
Manganese (Mn)	No universal marine threshold has been established.	mg/L	Assessment based on context
Copper (Cu)	0.0031	mg/L	Marine chronic criterion

The EPA values for copper and chromium (VI) are 3.1 µg/L and 50 µg/L, respectively, for chronic criteria in saltwater. These refer to concentrations of dissolved metals, not necessarily total metals.

d) Bacteriological reference thresholds

For coastal marine waters, microbiological indicators are used to assess contamination of fecal origin, particularly that which stems from domestic wastewater.

To this end, the main bacteriological indicators and their reference guideline values are presented in Table 5.

Table 5 presents the main bacteriological indicators, along with their reference guideline values, for assessing microbiological contamination in coastal marine waters.

Table 5. Reference values for bacteriological indicators in marine waters [17].

Bacteriological indicators	Indicative reference values	Units
Total coliforms	No universal health-based threshold	CFU/100mL
Fecal coliforms	≤100 (former indicative benchmark)	CFU/100mL
Intestinal enterococci	≤40 (target for very good quality, according to the WHO)	CFU/100mL

According to WHO recommendations (2021), marine bathing waters can be classified based on the concentrations of intestinal enterococci:

Table 6 presents the classification of marine bathing waters according to intestinal enterococci concentrations, based on the 95th percentile, and the associated levels of health risk, following WHO recommendations (2021).

Table 6. Classification of marine bathing waters based on intestinal enterococci concentrations and associated health risks [13].

Category	Concentration at the 95th percentile	Assessment
A	≤40 CFU/100mL	Low health risk
B	41 - 200 CFU/100mL	Low to moderate risk
C	201 - 500 CFU/100mL	Increased risk
D	More than 500 CFU/100mL	High health risk

These values serve as indicative benchmarks derived from various international references. They do not constitute a single standard applicable to all marine waters.

2.6. Data Processing

For each sampling point, the mean and standard deviation were calculated based on triplicate samples. Overall descriptive statistics (mean, standard deviation, range) were also computed for the entire set of 30 samples for each parameter. The mean value for each parameter was compared against the corresponding reference standard to assess compliance. As this study was designed as a descriptive and normative characterization—rather than a differential analysis of pollution sources (the latter having been the subject of separate work based on multivariate statistical analysis of the same data)—no statistical tests comparing the sampling stations were performed here. Analyses and graphical representations were carried out using Python 3.14 (pandas, matplotlib).

3. Results

3.1. Overview: Compliance with Reference Standards

Table 7 presents the overall mean (± standard deviation, n = 30) for each of the 16 measured parameters, the range of means per station (n = 10), the applicable reference standard, and the compliance status. Among the five physical parameters,

only turbidity exceeded the European standard of 5 NTU, and this occurred at only a minority of the stations. Regarding the four nutrients/anions, nitrite and sulfate concentrations significantly exceeded typical thresholds for drinking water at all ten stations, whereas nitrate and phosphate levels remained within permissible limits. Among the four metallic elements, only total iron exceeded the European standard (though it did not surpass the threshold set by the WHO for drinking water); concentrations of chromium, manganese, and copper remained well below the reference standards. From a bacteriological perspective, fecal and total coliforms were consistently detected (which does not meet the strict standard of 0 CFU/100mL applicable to drinking water, although it remains consistent with standards for bathing water regarding fecal coliforms), while fecal streptococci remained well below the European threshold for bathing water—set at 35 CFU/100mL—across all ten stations studied.

Table 7 summarizes the mean values and variability of the 16 physicochemical and bacteriological parameters measured across the ten sampling stations (E1 - E10), in comparison with international reference standards.

Table 7. Comparison of the mean values of the 16 parameters measured against international reference standards (n = 30 samples, 10 stations E1 - E10).

Parameter	Overall mean ± SD (n = 30)	Range of means by station (n = 10)	Reference standard	Status
Temperature (˚C)	29.24 ± 0.40	28.70 - 29.60	n.a.	-
pH	7.07 ± 0.24	6.51 - 7.36	6.5 - 8.5 (WHO, potability)	Compliant
Turbidity (NTU)	3.7 ± 1.5	2 - 6	≤5 (EU)	Non-compliant (1/10 stations > 5 NTU; 3/10 ≥ 5 NTU)
Salinity (ppt)	30.59 ± 1.39	27.99 - 32.64	n.a. (seawater)	-
Conductivity (µS/cm)	19556 ± 95	19430 - 19667	n.a. (seawater)	-
Nitrates (mg/L)	43.78 ± 5.56	36.24 - 49.56	≤50 (WHO/EU)	Compliant
Nitrites (mg/L)	1.56 ± 0.37	1.06 - 2.32	≤0.5 (WHO)	Non-compliant (10/10 stations)
Phosphates (mg/L)	0.0158 ± 0.0062	0.011 - 0.021	≤0.4 (eutrophication threshold)	Compliant
Sulfates (mg/L)	2297 ± 131	2238 - 2620	≤400 (WHO/EU, potability)	Non-compliant (10/10 stations)
Total iron (mg/L)	0.428 ± 0.066	0.36 - 0.49	≤0.06 (EU)/≤0.3 (WHO)	Non-compliant (EU)/ Compliant (WHO)
Total chromium (mg/L)	0.014 ± 0.015	0.000 - 0.030	≤0.05 (WHO)	Compliant
Manganese (mg/L)	0.009 ± 0.009	0.000 - 0.020	≤0.4 (WHO)/≤0.05 (EU)	Compliant
Copper (mg/L)	0.016 ± 0.009	0.010 - 0.030	≤2 (WHO)	Compliant
Fecal coliforms (CFU/100mL)	40.2 ± 15.3	14 - 62	0 (WHO, drinking water)/ ≤100 (bathing water)	Non-compliant (WHO)/ Compliant (swimming)
Total coliforms (CFU/100mL)	77.3 ± 30.0	32 - 137	0 (WHO, drinking water)	Non-compliant
Fecal streptococci (CFU/100mL)	4.90 ± 3.50	1 - 12	≤35 (EU, bathing water, enterococci)	Compliant

3.2. Turbidity and Physical Parameters

Mean turbidity ranged from 2 NTU (stations E5 and E10) to 6 NTU (station E2); only one station (E2) exceeded the European standard of 5 NTU, while two others (E4, E9) reached this limit value exactly (Figure 1). Temperature (29.2˚C ± 0.4˚C), pH (7.07 ± 0.24), and salinity (30.6 ± 1.4‰) remained consistent across the stations and were in line with the expected characteristics of tropical marine waters.

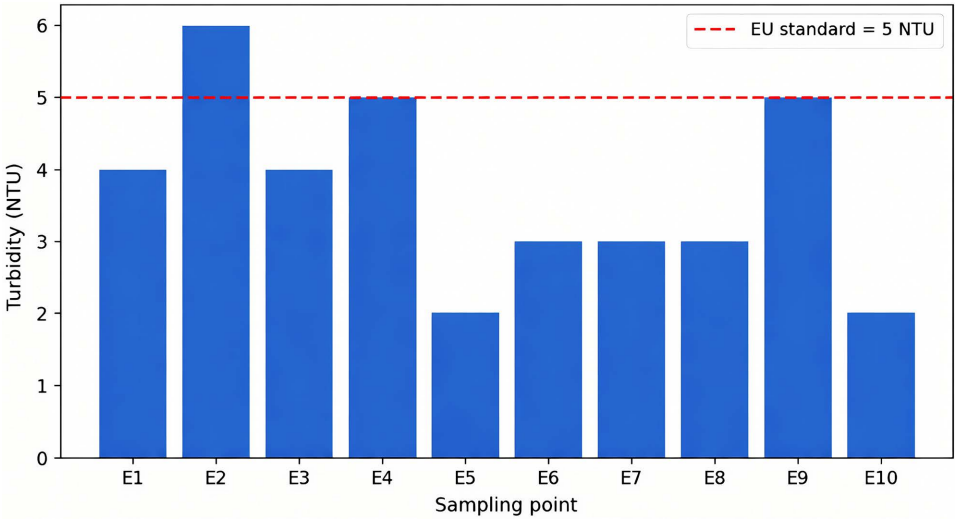

Figure 1. Mean turbidity per sampling station, compared to the European standard of 5 NTU.

3.3. Total Iron

Total iron showed the most pronounced metal contamination in the study, with station means ranging from 0.36 mg/L (E5) to 0.49 mg/L (E2). All values exceeded the European standard of 0.06 mg/L but—with the exception of station E5 (0.36 mg/L, a value very close to the limit)—remained below the WHO guideline value for drinking water, which is set at 0.3 mg/L (Figure 2). This relatively uniform contamination along the coastline could result either from diffuse inputs (urban runoff) or from the influence of the natural geochemistry of coastal sediments—a distinction that cannot be made based solely on the data from this study (see Discussion).

3.4. Sulfates

Sulfates exhibited the highest concentrations—and the most consistently non-compliant levels—in the entire study, with station means ranging from 2238 mg/L (E1) to 2620 mg/L (E2). These values are six to seven times higher than the 400 mg/L standard set for drinking water, and this applies to all ten stations (Figure 3). However, this non-compliance must be interpreted with particular caution: seawater naturally contains sulfates at concentrations ranging from 2500 to 2700 mg/L, due to its specific ionic composition. Consequently, a drinking water standard designed for fresh water cannot be directly applied to a marine environment without considering the specific context (see Discussion, section 4).

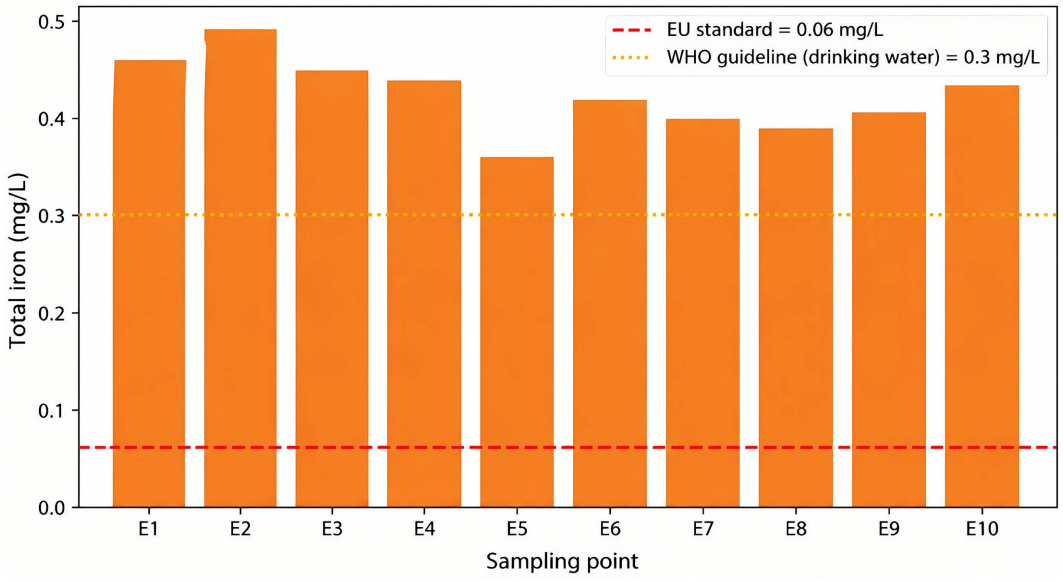

Figure 2. Mean total iron content per sampling station, compared with drinking water standards established by Europe (0.06 mg/L) and the WHO (0.3 mg/L).

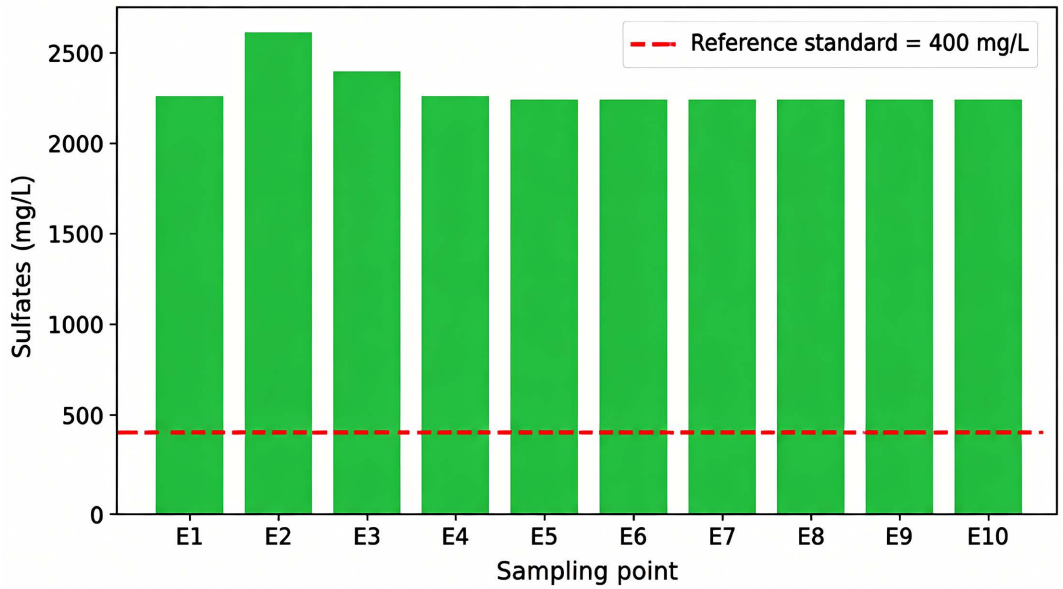

Figure 3. Mean sulfate concentrations by sampling station, compared to the reference potability threshold of 400 mg/L.

3.5. Chromium, Manganese, and Copper

Unlike iron, the other three metallic elements measured remained at very low levels—well below reference standards—across all stations: total chromium 0.014 ± 0.015 mg/L (range of station means: 0 - 0.03 mg/L; WHO standard: 0.05 mg/L), manganese 0.009 ± 0.009 mg/L (range: 0 - 0.02 mg/L; WHO standard: 0.4 mg/L), and copper 0.016 ± 0.009 mg/L (range: 0.01 - 0.03 mg/L; WHO standard: 2 mg/L) (**Figure 4**). Consequently, these three elements currently pose no concerns regarding water quality along the Bonfi coastline.

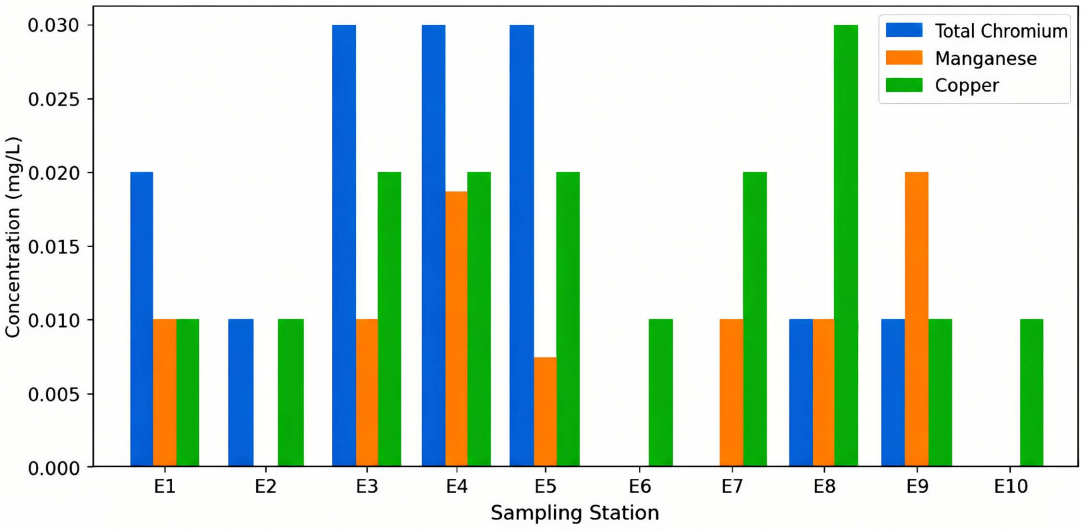

Figure 4. Mean concentrations of total chromium, manganese, and copper by monitoring station.

3.6. Bacteriological Indicators

Fecal coliforms (mean: 40.2 ± 15.3 CFU/100mL; range of station means: 14 - 62 CFU/100mL) and total coliforms (77.3 ± 30.0 CFU/100mL; range: 32 - 137 CFU/100mL) were detected at all ten stations, though none exceeded the 100 CFU/100mL threshold typically used as a guideline for bathing waters (**Figure 5**). Fecal streptococci remained at very low levels (4.9 ± 3.5 CFU/100mL; range: 1 - 12 CFU/100mL)—well below the European threshold of 35 CFU/100mL established for enterococci in bathing waters—across all stations. These results indicate detectable but moderate fecal contamination, with no alarming levels of bacteriological pollution at the time of the sampling campaign.

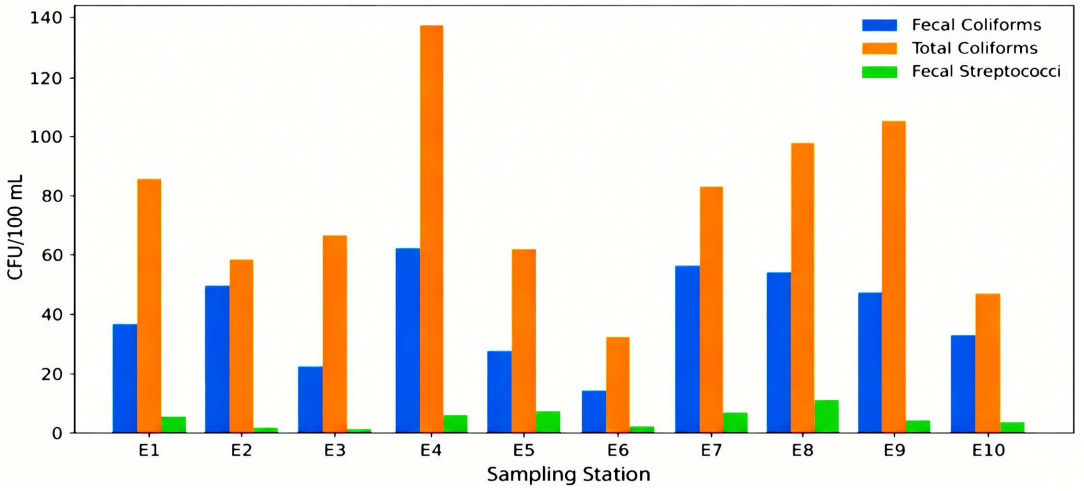

Figure 5. Averages of bacteriological indicators by sampling station (fecal coliforms, total coliforms, fecal streptococci).

The presence of fecal coliforms, total coliforms, and fecal streptococci across all sampling stations indicates widespread microbiological contamination along the

Bonfi coastline. The relatively low concentrations of fecal coliforms (40.2 ± 15.3 CFU/100mL) and fecal streptococci (4.9 ± 3.5 CFU/100mL) suggest moderate fecal contamination at the time of sampling. However, the higher concentrations of total coliforms (77.3 ± 30.0 CFU/100mL) point to a more significant bacterial presence, likely linked to urban and domestic discharges.

These findings may be attributed to wastewater discharge, urban runoff, and human activities occurring along the coastline. Despite the low concentrations observed, the widespread presence of these indicators highlights the existence of potential contamination sources and justifies regular microbiological monitoring.

4. Discussion

This integrated characterization of the waters off the Bonfi coastline reveals a contrasting contamination profile: metal contamination essentially limited to iron, high mineralization in terms of sulfates and nitrites, and a detectable but moderate level of bacteriological contamination at the time of sampling. This profile differs from that observed in other West African coastal areas subject to greater or more diverse industrial pressure—where several trace metals (lead, cadmium, cobalt, nickel, zinc) simultaneously exceed reference standards, as has been demonstrated for the Konkouré estuary in Guinea [1], the Dakar coastline [3], and the Lagos Lagoon [4].

The relatively low concentrations of chromium, manganese, and copper observed here may reflect more limited or localized industrial pressure on this specific segment of the Conakry coastline at the time of the study. This contrast is even more pronounced when compared to the Ébrié Lagoon in Abidjan (Côte d'Ivoire), where intense industrial and domestic pressure—with over 80% of industries located directly along the lagoon's edge, discharging untreated effluents into it—results in concentrations of coliforms and fecal streptococci several orders of magnitude higher than those measured off the Bonfi coast [18]-[20]. Consequently, at the time of this study, the Bonfi coastline was in a significantly less degraded state than other heavily industrialized coastal areas in West Africa.

Iron contamination, while exceeding European standards, remained close to the potability threshold established by the WHO; this finding aligns with levels reported in various watercourses and coastal zones across Africa that are subject to diffuse urban inputs rather than a major, localized source of industrial pollution [21]. The origin of this contamination could be natural (related to the geochemistry of coastal sediments, which are often rich in iron oxides in tropical environments) or anthropogenic (urban runoff, corrosion of port infrastructure). To distinguish between these two hypotheses, further sediment analysis and comparisons with unexposed reference sites would be required—an approach previously used to differentiate natural from anthropogenic inputs in other coastal contexts [22] [23].

The massive and systematic exceedance of the potability standard for sulfates (by a factor of 6 to 7) highlights a significant methodological limitation, previously

noted in section 2.3: the standards applied in this study—in the absence of specific Guinean benchmarks for marine waters—were originally designed for freshwater intended for human consumption [13]. Seawater, however, naturally contains sulfate concentrations well above this threshold, simply by virtue of its ionic composition. Consequently, this result should not be interpreted as industrial sulfate pollution, but rather as a clear illustration of why applying potability standards directly to a marine environment is inappropriate. It underscores the need—discussed further on—for a quality reference framework specifically tailored to Guinean coastal waters.

The absence of concerning levels of bacteriological contamination—indicated by concentrations of fecal coliforms and fecal streptococci that fall below the reference thresholds established for bathing waters across all studied sites—is a relatively reassuring finding. However, these observations should be interpreted with caution, as the microbiological contamination of aquatic environments can fluctuate based on climatic conditions, precipitation, the influx of domestic wastewater, and surface runoff. Consequently, the results obtained reflect the sanitary conditions of the environment at the time of sampling and do not necessarily rule out the possibility of isolated, intermittent episodes of contamination [13].

In this regard, fecal streptococci are valuable complementary indicators of fecal contamination, as their environmental persistence may differ from that of coliforms, making them useful for assessing microbial contamination over time and across seasons [24] [25].

A single, one-off sampling campaign cannot rule out the risk of more pronounced fecal contamination at other times of the year, particularly during the rainy season, when urban runoff intensifies [26].

From an operational perspective, this integrated characterization highlights three concrete priorities, consistent with the scope of this study: first, the development of a national or regional quality standard for coastal marine waters, tailored to the natural composition of seawater (specifically regarding sulfates and salinity)—a prerequisite for the rigorous interpretation of future monitoring campaigns; second, the identification and management of iron sources in the coastal environment—even in cases where the WHO thresholds for drinking water are not exceeded—in accordance with the precautionary principle; and third, the implementation of regular, seasonal bacteriological monitoring—particularly during periods of heavy rainfall and intense fishing activity—in order to detect potential spikes in fecal contamination that might be missed by a one-off study such as the one presented here.

5. Study Limitations

Several limitations are worth noting. First—and this is the most significant limitation for interpreting the results—the absence of Guinean or West African standards specific to coastal marine waters necessitated the use of standards intended for drinking water or bathing water (freshwater for human consumption, Euro-

pean bathing water standards). Consequently, it is difficult to gauge the true health or environmental implications of certain instances where limits were exceeded (notably regarding sulfate levels). Second, the study is based on a single sampling campaign, which fails to account for seasonal variations in water quality—particularly concerning bacteriological indicators, the levels of which can fluctuate significantly between the dry and rainy seasons. Third, the number of replicates per station (n = 3) is too limited to allow for an accurate estimate of variability within the stations themselves. Fourth, this study did not include an analysis of sediments, which would have helped to better distinguish between natural and anthropogenic contributions to iron contamination.

Finally, no inferential statistical analysis of pollution sources (such as correlations, principal component analysis, or classification) was performed in this study, which deliberately focused on a descriptive and normative characterization. Such an analysis, based on the same dataset, is the subject of a separate study dedicated to identifying pollution sources through multivariate analysis.

6. Conclusion

The integrated characterization of coastal waters off Bonfi reveals metal contamination limited to iron, high concentrations of sulfates and nitrites—the interpretation of which is complicated by the lack of reference standards for the marine environment—as well as detectable but moderate bacteriological contamination at the time of the study. None of the four metals analyzed reaches levels of concern when compared to World Health Organization (WHO) standards for drinking water. This approach—ranging from multiparametric characterization to the formulation of concrete proposals for action (such as developing a reference framework tailored to marine environmental quality, controlling iron inputs, and establishing seasonal bacteriological monitoring)—provides a useful foundation for the future monitoring and management of this coastline, especially given the scarcity of published local data.

Author Contributions

The first author conceived and conducted the study, collected the data, and drafted the manuscript. The first, second, and third authors contributed to data analysis and interpretation. The fourth author contributed to the critical review and final validation of the manuscript. All authors read and approved the final version of the manuscript.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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