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Geochemical controls on hydrocarbon distribution and associated bacterial assemblages in petroleum-influenced mangrove sediments, northeastern Brazil

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Abstract:
Mangrove sediments function as efficient sinks for hydrophobic contaminants due to their fine-grained texture, elevated organic matter content, and low hydrodynamic energy. In petroleum-influenced coastal systems, identifying the geochemical controls that regulate hydrocarbon retention is essential for understanding contaminant persistence and environmental behavior. This study investigated sediment geochemistry and associated bacterial assemblages in a chronically oil-impacted mangrove system in São Francisco do Conde, northeastern Brazil. Total petroleum hydrocarbons (TPH), total organic carbon (TOC), grain-size distribution, and hydrocarbon fractions were quantified and evaluated using correlation analysis and principal component analysis (PCA). TPH concentrations varied markedly among sampling sites, with the highest values observed in the São Francisco sector. A strong and statistically significant positive correlation between TOC and TPH ($r = 0.864$, $p = 0.012$) indicates that sedimentary organic carbon exerts a primary control on hydrocarbon distribution. Although silt–clay fractions predominated across samples, textural parameters alone did not explain the observed variability. Multivariate ordination revealed a structured geochemical gradient separating sectors primarily along hydrocarbon-associated axes. High-throughput 16S rRNA gene sequencing demonstrated spatial variability in bacterial community composition consistent with the geochemical gradient. The concordance between organic carbon content, hydrocarbon accumulation,

and community structuring highlights the importance of sedimentary carbon dynamics in regulating hydrocarbon fate in tropical mangrove environments.

Keywords: Mangrove sediments, Petroleum hydrocarbons, Environmental geochemistry, Total organic carbon, Sediment contamination

1 INTRODUCTION

Mangrove ecosystems are highly productive coastal environments that function as dynamic biogeochemical interfaces between terrestrial and marine systems. They play a central role in nutrient cycling, sediment stabilization, shoreline protection, and long-term carbon sequestration, thereby contributing substantially to coastal carbon storage and elemental cycling (Alongi, 2014; Alongi, 2022). Owing to their fine-grained sediments, elevated organic matter content, and generally low hydrodynamic energy, mangroves efficiently retain both natural and anthropogenic substances, including hydrocarbons and trace metals (Tam & Wong, 2000; Marchand et al., 2011).

Despite their ecological importance, mangroves located near urban and industrialized regions are increasingly exposed to multiple anthropogenic stressors, including industrial effluents, sewage discharge, metal contamination, and chronic petroleum inputs. Such pressures can modify sediment geochemistry and potentially influence benthic microbial assemblages responsible for key biogeochemical processes (Hatje et al., 2012; Pereira et al., 2020). Petroleum hydrocarbons are of particular concern in mangrove sediments because their hydrophobic properties promote sorption to organic-rich and fine mineral fractions, enhancing environmental persistence and limiting dispersion (Head et al., 2006; Volkman et al., 2013).

In northeastern Brazil, the Baía de Todos os Santos represents one of the largest tropical embayments in the South Atlantic and simultaneously hosts one of the country's oldest petrochemical and port complexes. Since the mid-twentieth century, refining activities, maritime transport, and associated industrial operations have contributed to recurrent hydrocarbon inputs into estuarine and coastal compartments (Hatje et al., 2012). Previous investigations have reported elevated concentrations of total petroleum hydrocarbons (TPH) and trace metals in sediments from different sectors of the bay, indicating sustained anthropogenic pressure and geochemical heterogeneity at local scales (Pereira et al., 2020).

Microbial communities are fundamental to the ecological functioning of mangrove sediments, where they drive organic matter mineralization, nitrogen transformations, sulfate reduction, and the biodegradation of hydrocarbons (Head et al., 2006; Nogales et al., 2011). In petroleum-influenced environments, selective pressures associated with hydrocarbon availability and redox conditions may favor taxa capable of hydrocarbon utilization or tolerance, including members of the Gammaproteobacteria and sulfate-reducing bacterial lineages (Head et al., 2006; Kostka et al., 2011). Shifts in community composition along contamination gradients have therefore been interpreted as reflecting the combined influence of geochemical constraints and microbial adaptive capacity.

High-throughput sequencing of the 16S rRNA gene has substantially advanced the characterization of sediment microbiomes by enabling culture-independent assessments of community composition and diversity (Caporaso et al., 2012; Knight et al., 2018). When combined with multivariate statistical approaches, these data allow exploratory evaluation of covariation between microbial assemblages and environmental parameters, including organic matter content and hydrocarbon concentrations. Studies conducted in tropical mangrove systems frequently report the dominance of bacterial phyla such as Proteobacteria, Bacteroidota, Actinobacteriota, Firmicutes, and Chloroflexi, encompassing functional groups associated with sulfur and nitrogen cycling as well as hydrocarbon transformation (Andreote et al., 2012; Mendes & Tsai, 2014).

Although mangroves within the Baía de Todos os Santos have been investigated from a geochemical perspective, detailed taxonomic characterization of bacterial communities in petroleum-influenced sediments from São Francisco do Conde remains limited. In particular, integrative analyses examining how bacterial assemblage structure covaries with sediment hydrocarbon composition under conditions of chronic contamination are still scarce for this region.

In this study, we characterized bacterial communities in mangrove sediments using Illumina-based 16S rRNA gene sequencing and examined patterns of taxonomic composition in relation to sediment geochemical parameters, including total petroleum hydrocarbons and hydrocarbon fractions. By applying multivariate exploratory analyses, we evaluated whether spatial variation in bacterial assemblages is directionally consistent with observed geochemical heterogeneity across sampling sites. This approach provides insight into community–environment covariation in a chronically oil-influenced tropical mangrove system.

2 MATERIALS AND METHODS

2.1 Study Area

The study area is located in the municipality of São Francisco do Conde, Bahia State, northeastern Brazil, within the northeastern sector of the Baía de Todos os Santos. The investigated mangrove system covers approximately 265 ha and forms part of a broader estuarine complex subjected to long-term anthropogenic influence.

The region has undergone substantial land-use modification associated with industrial expansion, petrochemical activities, port operations, and urban development. Approximately 182 ha of the original mangrove and adjacent Atlantic Forest vegetation have been affected by deforestation and landscape alteration. These activities have contributed to changes in local geomorphology and to the introduction of petroleum-derived contaminants into estuarine sediments.

As a result, the mangrove system exhibits spatial heterogeneity in sediment characteristics and contamination levels, reflecting varying degrees of anthropogenic pressure. This environmental variability provides a framework for evaluating patterns of sediment geochemistry and associated bacterial community composition across sites subjected to contrasting hydrocarbon influence. The location of the study area and sampling sites is presented in Figure 1.

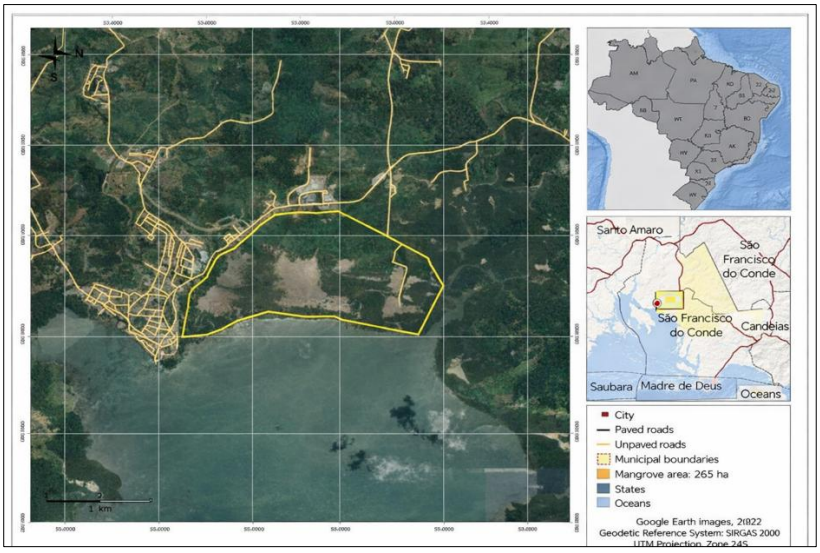


Figure 1. Location of the study area in São Francisco do Conde, Bahia State, northeastern Brazil, showing the mangrove system and sediment sampling sites.

2.2 Sample Collection

Sediment sampling was conducted at seven distinct sites within the study area, comprising three sites in São Francisco (SF1–SF3) and four sites in Baixa Fria (BF1–BF4). Surface sediment samples (0–10 cm depth) were manually collected using sterile stainless-steel spatulas and immediately transferred to autoclaved glass containers.

Samples were maintained under refrigerated conditions during transport to the Center of Excellence in Geochemistry, Petroleum, Energy and Environment (LEPETRO), Institute of Geosciences, Federal University of Bahia (UFBA). Upon arrival, sediments were stored at 4 °C until further laboratory processing.

2.3 DNA Sequencing

For molecular analyses, sediment aliquots were transferred to sterile 1.5 mL DNase- and RNase-free microtubes containing DNA/RNA preservative solution (Zymo Research Corporation). Samples were transported under refrigerated conditions to a commercial sequencing facility (Neoprospecta S.A., Brazil), where DNA extraction, library preparation, sequencing, and primary bioinformatic processing were performed.

Bacterial community composition was assessed through high-throughput sequencing of the V3–V4 hypervariable regions of the 16S rRNA gene. PCR amplification employed the universal primers 341F (5′-CCTACGGGRSGCAGCAG-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′). Sequencing was performed on an Illumina MiSeq platform using paired-end reads.

2.4 Bioinformatic Processing

Raw FASTQ files were processed using the Sentinel bioinformatics pipeline (Neoprospecta S.A.). Initial sequence quality assessment was conducted using FastQC v.0.11.8 (Andrews, 2010). Primer sequences and low-quality bases were removed using a Phred quality threshold of 20.

For paired-end reads, forward (R1) and reverse (R2) sequences were merged using PANDAseq v.2.11 (Masella et al., 2012). Sequence clusters with abundances lower than five reads were excluded from downstream analyses to reduce potential sequencing artifacts and low-frequency noise.

Taxonomic assignment was performed using BLASTn v.2.6.0+ (Altschul et al., 1990) against a curated proprietary reference database. Species-level classification was assigned at a sequence identity threshold of 99%.

2.5 Geochemical Analyses

Sediment samples were analyzed for total organic carbon (TOC), nitrogen, grain-size distribution, total petroleum hydrocarbons (TPH), and polycyclic aromatic hydrocarbons (PAHs).

For metal and inorganic analyses, sediments were collected using plastic scoops and stored in hermetically sealed polyethylene bags. For organic compound analyses, samples were collected using stainless-steel scoops and stored in glass containers previously decontaminated with 10% Extran® solution for 24 h. Glassware was subsequently rinsed with tap water, distilled water, and ultrapure water, and dried at 100 °C.

All samples were maintained under refrigerated conditions from collection until laboratory analysis.

2.6 Determination of Total Organic Carbon (TOC)

Total organic carbon (TOC) and total nitrogen were determined following a methodology adapted from EPA-NCE (2002). Approximately 1 g of dried sediment was ground, sieved to <0.177 mm (80 mesh), and placed in porous ceramic crucibles.

Carbonates were removed by treatment with heated 1 mol L^{-1} HCl for approximately 1 h. After acidification, samples were rinsed with hot distilled water until complete removal of chloride ions, verified using $AgNO_3$ solution.

Samples were dried at 80 °C, cooled in a desiccator, and weighed repeatedly until constant mass was achieved. TOC and nitrogen concentrations were measured using a LECO 628 CN elemental analyzer equipped with an infrared detector for carbon quantification.

2.6 Grain-Size Analysis

Grain-size distribution was determined following a methodology adapted from EMBRAPA (1997). Approximately 3 g of sediment were treated with hydrogen peroxide (H_2O_2) to remove organic matter. After digestion, samples were dispersed with sodium hexametaphosphate solution and agitated on an orbital shaker for 4 h to prevent particle aggregation.

Particle-size fractions were determined using a laser diffraction granulometer (Cilas 1064). Grain-size statistical parameters were calculated using GRADSTAT software, and sediment classification followed the criteria of Folk and Ward (1957).

2.7 Determination of Total Petroleum Hydrocarbons (TPH) and Polycyclic Aromatic Hydrocarbons (PAHs)

Extraction of soluble organic matter followed USEPA Method 3550C (2007), with adaptations. Approximately 50 g of homogenized sediment were mixed with diatomaceous earth and subjected to accelerated solvent extraction (ASE) using dichloromethane at 150 °C and 1500 psi for three extraction cycles of 15 min each.

Extracts were concentrated under reduced pressure using a rotary evaporator (Büchi Rotavapor R-210) to volumes below 500 µL. Total petroleum hydrocarbons (TPH) were quantified by gas chromatography with flame ionization detection (GC-FID; Agilent 7890B), following the procedure described by Kaufman et al. (1990).

Fractionation of extracts was performed using the SARA method, separating saturated hydrocarbons (F1), aromatic hydrocarbons (F2), and polar compounds (F3; resins and asphaltenes). Silica gel columns (activated at 450 °C for 4 h) were used for fractionation. Sequential elution was performed with n-hexane (F1), n-hexane:dichloromethane (4:1, v/v; F2), and dichloromethane:methanol (4:1, v/v; F3).

The aromatic fraction (F2) was spiked with deuterated internal standards (d_8-naphthalene, d_{10}-acenaphthene, d_{10}-phenanthrene, d_{12}-chrysene, and d_{12}-perylene) and analyzed by gas chromatography–mass spectrometry (GC–MS; Agilent 7820A) equipped with a DB-5 capillary column (30 m).

3 RESULTS AND DISCUSSION

3.1 Taxonomic Structure of Bacterial Communities

Amplicon sequencing of the 16S rRNA gene revealed that sediment samples from the mangrove areas of São Francisco do Conde were dominated by bacterial taxa affiliated with the genera Acinetobacter, Bacillus, Marinobacter, Anaerolinea, Vibrio, and Rhodobacter. Relative abundances varied between the São Francisco (SF) and Baixa Fria (BF) sites. In all samples, members of the domain Bacteria predominated, consistent with the typical microbial structure reported for coastal and estuarine sediments.

In the São Francisco sector, comparatively higher relative abundances of Marinobacter, Acidimicrobium, and Anaerolinea were observed. These genera are frequently reported in marine and mangrove sediments and are commonly associated with organic-rich and redox-stratified environments (Andreote et al., 2012; Mendes & Tsai, 2014). Members of the genus Marinobacter have been widely detected in saline environments and in sediments influenced by petroleum hydrocarbons, where they are often linked to hydrocarbon transformation processes (Head et al., 2006; Handley & Lloyd, 2013). Likewise, representatives of the phylum Chloroflexi, including Anaerolinea, are commonly described in anoxic or suboxic sediments and have been associated with anaerobic organic matter degradation pathways (Yamada et al., 2006; Dutta et al., 2020).

In contrast, samples from the Baixa Fria area exhibited a more heterogeneous taxonomic profile, with notable contributions from Acinetobacter, Bacillus, Vibrio, and Rhodobacter. These genera are widely distributed in coastal sediments and estuarine systems and are often reported in environments subjected to fluctuating redox conditions and variable organic matter inputs (Nogales et al., 2011; Mendes & Tsai, 2014). The detection of these taxa in both sectors suggests the coexistence of bacterial groups with broad ecological tolerances across sites with differing geochemical characteristics.

It is important to note that functional interpretations in the present study are inferred solely from taxonomic affiliation. Although genera such as Marinobacter and Acinetobacter have been previously associated with hydrocarbon-rich environments (Head et al., 2006; Handley & Lloyd, 2013), no direct functional gene analyses were conducted. Therefore, potential roles in hydrocarbon transformation are discussed here only in the context of previously reported ecological associations rather than demonstrated metabolic activity.

Overall, the bacterial assemblages observed across the study area reflect patterns commonly reported for tropical mangrove sediments, where Proteobacteria and other metabolically versatile lineages dominate under conditions of elevated organic matter and variable redox potential (Andreote et al., 2012; Mendes & Tsai, 2014). Differences in relative abundance between sites suggest spatial variability in community composition that may be associated with local geochemical heterogeneity. Subsequent multivariate analyses were therefore conducted to explore potential covariation between sediment hydrocarbon composition and bacterial assemblage structure.

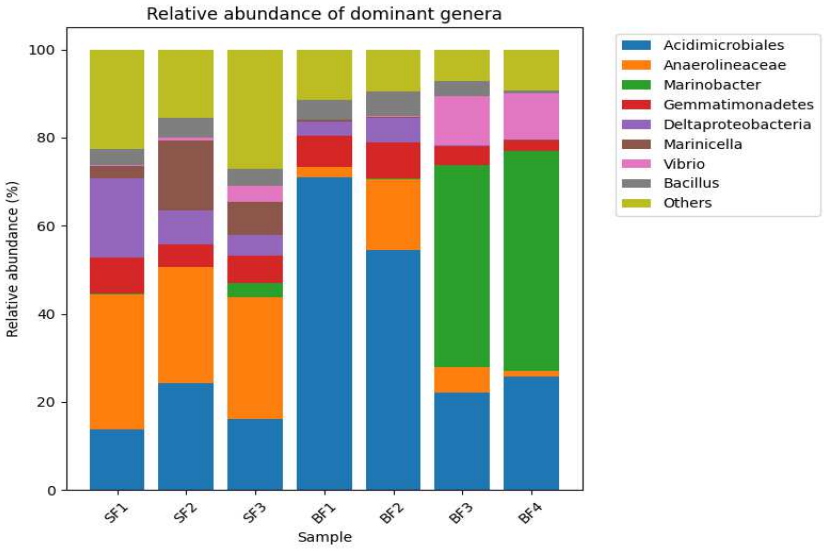


Figure 2. Relative abundance of the most abundant bacterial genera in sediment samples from the São Francisco and Baixa Fria mangrove areas.

Total petroleum hydrocarbon (TPH) concentrations varied markedly among sediment samples, indicating pronounced spatial geochemical heterogeneity across the study area (Figure 3). After normalization to dry weight (mg kg^{-1}), the highest TPH concentrations were recorded in the São Francisco (SF) series, with SF3 presenting the maximum value, followed by SF2 and SF1. In contrast, sediments from the Baixa Fria (BF) sector exhibited substantially lower concentrations, with only BF4 showing detectable TPH levels, whereas BF1–BF3 displayed values close to analytical detection limits.

The elevated TPH concentrations observed in SF sediments are consistent with the physicochemical characteristics typically associated with mangrove substrates. Fine-grained matrices enriched in organic matter enhance the sorptive partitioning of

hydrophobic petroleum compounds, promoting their retention and environmental persistence (Volkman et al., 2013; Pereira et al., 2020). Under low-energy depositional conditions, such as those prevailing in mangrove environments, reduced hydrodynamic flushing further limits contaminant dispersion, favoring local accumulation.

In contrast, the comparatively low TPH levels observed in most BF samples may reflect either reduced hydrocarbon inputs or differences in sedimentological and hydrodynamic regimes that constrain contaminant retention. Variations in grain-size composition, organic carbon content, and tidal exchange can strongly influence hydrocarbon distribution patterns in estuarine systems by controlling both sorption capacity and weathering dynamics.

Although microbial-mediated attenuation pathways, including aerobic oxidation of n-alkanes and facultative degradation of low-molecular-weight aromatic hydrocarbons, are well documented in coastal sediments (Head et al., 2006; Prince et al., 2017), the present study did not directly quantify functional genes, enzymatic activity, or metabolic rates. Therefore, any inference regarding biodegradation processes is based solely on concentration patterns and should be interpreted cautiously.

Taken together, the pronounced contrast in TPH concentrations between the SF and BF sectors (Figure 3) establishes a well-defined environmental gradient of hydrocarbon exposure. This gradient provides a suitable framework for exploratory assessment of potential covariation between sediment geochemistry and bacterial community structure, without presuming direct causal relationships.

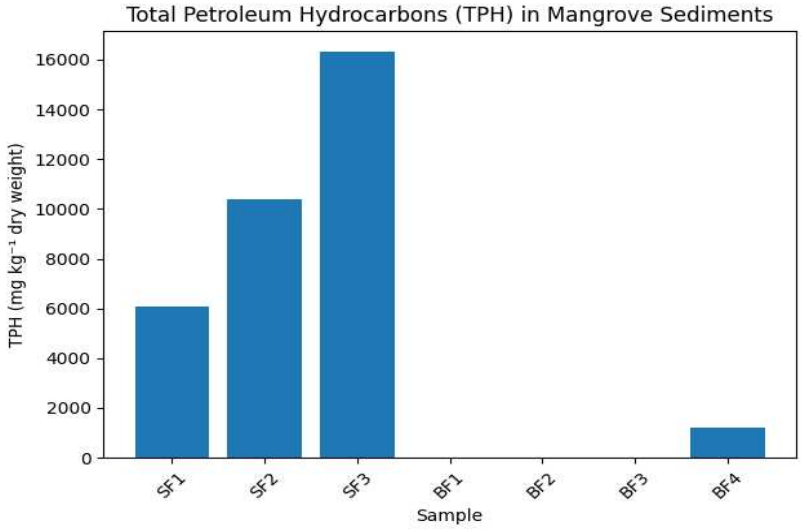


Figure 3. Quantification of total petroleum hydrocarbons (TPH) in sediment samples.

Overall, the results indicate pronounced spatial heterogeneity in hydrocarbon distribution, reflecting the combined influence of depositional setting, sediment composition, and organic matter dynamics within the estuarine system. In contrast to what might be expected under uniform contamination scenarios, the highest TPH concentrations were observed in the São Francisco (SF) sector, whereas most Baixa Fria (BF) samples exhibited comparatively low hydrocarbon levels. This pattern suggests that local sedimentological and geochemical controls, rather than simple proximity to anthropogenic sources, are key drivers of hydrocarbon retention.

The predominance of silt–clay fractions across all samples (Figure 4) indicates low-energy depositional conditions characteristic of mangrove environments. Fine-grained sediments increase specific surface area and enhance the sorptive capacity of the sediment matrix, thereby promoting the accumulation and persistence of hydrophobic petroleum compounds. However, despite the relatively similar textural composition among sites, TPH concentrations differed substantially between sectors, indicating that grain size alone does not fully explain hydrocarbon distribution.

A strong and statistically significant positive correlation was observed between total organic carbon (TOC) and total petroleum hydrocarbons (TPH) (Pearson $r = 0.864$, $p = 0.012$, $n = 7$), indicating a robust association between hydrocarbons and sedimentary organic matter. Organic carbon provides binding sites for nonpolar compounds, increasing their apparent environmental persistence through organic phase partitioning. In contrast, weak correlations between TPH and individual grain-size fractions suggest that sediment texture exerts a secondary influence compared to organic matter content.

These findings are consistent with organic partitioning models proposed for coastal sediments (Wang et al., 2019; Zhuang et al., 2022), in which hydrocarbon distribution is primarily governed by the quantity and quality of sedimentary organic carbon rather than by granulometric parameters alone. Consequently, the observed spatial gradient in TPH across the study area likely reflects differences in organic carbon accumulation and local depositional dynamics, rather than a straightforward gradient of anthropogenic input intensity.

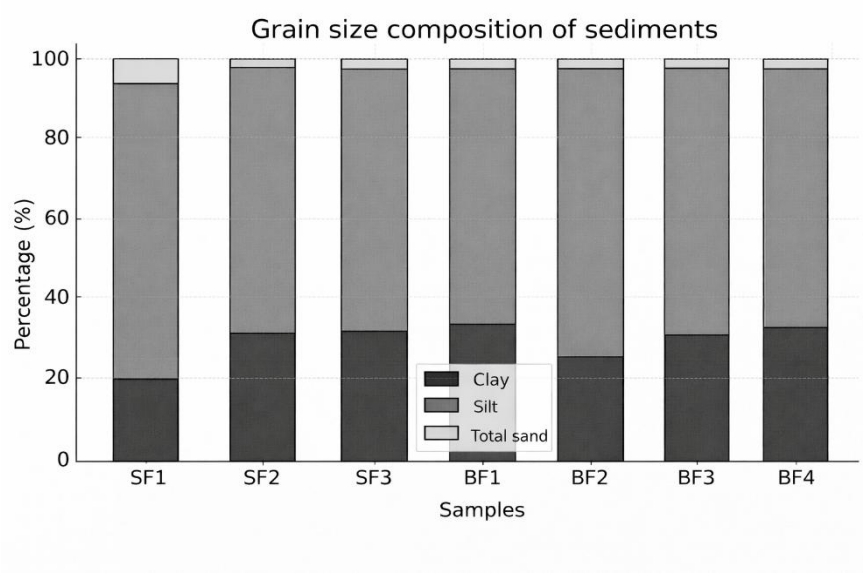


Figure 4. Grain-size composition of sediment samples.

These findings are consistent with previous studies highlighting the dominant role of sedimentary organic matter in controlling hydrocarbon retention in coastal environments. As discussed by Volkman et al. (2013) and Pereira et al. (2020), sediments with elevated total organic carbon (TOC) contents exhibit enhanced capacity to accumulate petrogenic compounds due to the preferential partitioning of hydrophobic hydrocarbons into the organic phase. This sorptive process increases the apparent environmental persistence of these compounds by limiting their mobility and dilution within the sediment column.

Beyond total concentration, the compositional quality of organic matter also influences hydrocarbon dynamics. Humic substances and aromatic macromolecular fractions provide high-affinity sorption domains that can further stabilize petroleum-derived compounds and reduce their bioavailability for microbial transformation. Such interactions may decouple total hydrocarbon concentration from actual biodegradation potential, particularly in fine-grained, organic-rich sediments.

The strong positive association observed between TPH and TOC in both the SF and BF sectors supports the interpretation that organic carbon content is a primary regulator of hydrocarbon distribution in the studied sediments. This relationship likely reflects the combined influence of organic matter inputs, depositional processes, and local redox conditions that govern carbon preservation and contaminant stabilization. Sites characterized by higher TOC values, such as SF2 and SF3, exhibited correspondingly

higher TPH concentrations, whereas sandier and comparatively carbon-poor sites, including BF1 and BF4, displayed reduced hydrocarbon accumulation.

These patterns align with organic partitioning frameworks described by Prince et al. (2017) and Wang et al. (2019), which attribute hydrocarbon retention primarily to the chemical affinity between nonpolar compounds and the sedimentary organic matrix rather than to granulometric controls alone. Collectively, the data indicate that organic carbon exerts a stronger influence on hydrocarbon distribution than sediment texture per se within this mangrove system.

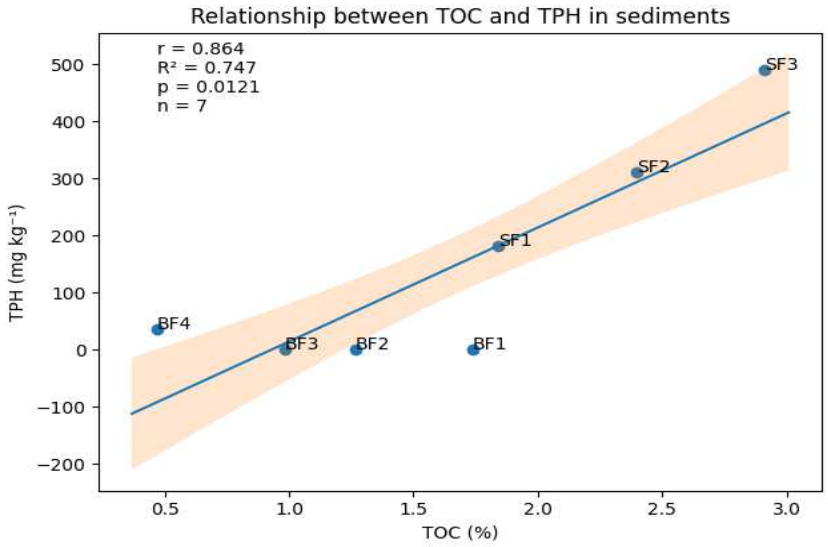


Figure 5. Relationship between total organic carbon (TOC) content and total petroleum hydrocarbons (TPH) in sediment samples.

The relationship between total organic carbon (TOC) and total petroleum hydrocarbons (TPH) is illustrated in Figure 5 and reveals a strong positive linear association across sampling sites. Samples with higher TOC content, particularly SF2 and SF3, exhibited markedly elevated TPH concentrations, whereas sediments with lower TOC values, especially those from the BF sector, clustered toward the lower end of the gradient.

Pearson correlation analysis demonstrated a strong and statistically significant positive correlation between TOC and TPH ($r = 0.864$, $p = 0.012$, $n = 7$), indicating that organic carbon content exerts a substantial control on hydrocarbon distribution within the studied sediments. Although the sample size remains limited, the statistical significance and consistency of the trend across independent sites support the interpretation that organic phase partitioning represents a dominant mechanism governing hydrocarbon retention.

Importantly, the dispersion pattern does not appear to be driven by a single influential outlier. SF3, which presented the highest TOC content, also exhibited the highest TPH concentration, but intermediate values observed in SF1 and SF2 reinforce the continuity of the gradient rather than a stepwise separation between groups.

These findings provide empirical support for partition-based models of hydrocarbon retention in coastal sediments (Prince et al., 2017; Wang et al., 2019), in which organic matter content plays a more influential role than granulometric parameters in determining contaminant accumulation. Accordingly, the observed geochemical gradient across the study area appears structurally coupled to sedimentary carbon dynamics rather than being solely a function of sediment texture.

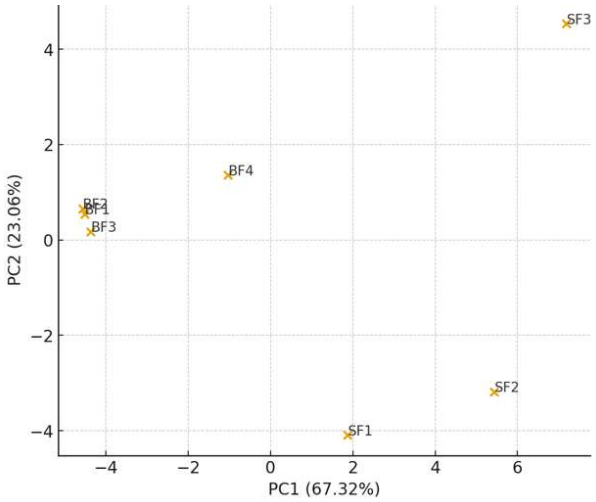


Figure 6. Principal component analysis (PCA) based on hydrocarbon-related geochemical variables in sediment samples. PC1 and PC2 explain 67.32% and 23.06% of the total variance, respectively.

The PCA ordination (Figure 6) reveals a clear spatial structuring of sediment samples along the first principal component. Together, PC1 and PC2 account for 90.38% of the total variance, indicating that the first two axes effectively summarize the dominant gradients in the geochemical dataset.

Separation along PC1 represents the primary hydrocarbon-related gradient, with São Francisco (SF) samples positioned predominantly on the positive side of the axis, whereas Baixa Fria (BF) samples cluster on the negative side. This distribution is consistent with the higher TPH and TOC values observed in SF sediments and supports the interpretation of a structured environmental gradient across the study area.

Dispersion along PC2 reflects secondary variability within groups. SF3 is clearly separated in the upper-right quadrant, indicating distinct geochemical characteristics relative to the remaining samples, while SF2 and SF1 occupy the lower-right quadrant, suggesting intra-sector heterogeneity within the SF group. In contrast, BF1, BF2, and BF3 form a tight cluster on the left side of the ordination space, indicating relatively homogeneous geochemical signatures. BF4 shows a moderate displacement toward positive PC2 values, suggesting slight differentiation from the main BF cluster.

Overall, the PCA reinforces the existence of spatial geochemical heterogeneity structured primarily along a hydrocarbon-associated gradient, while avoiding inference of direct causal mechanisms. The ordination provides a multivariate framework for subsequent evaluation of potential covariation between sediment geochemistry and bacterial community composition.

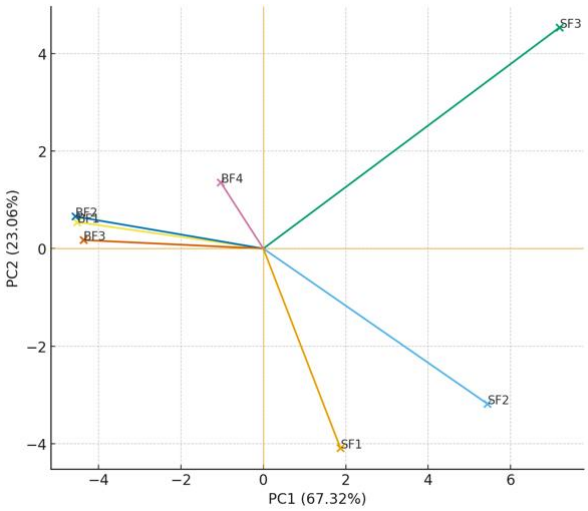


Figure 7. Principal component analysis (PCA) of hydrocarbon-related geochemical variables showing sediment samples represented as vectors originating from the ordination centroid. PC1 and PC2 explain 67.32% and 23.06% of the total variance, respectively.

The vector-based PCA representation (Figure 7) further emphasizes the spatial structuring of sediment samples along the primary geochemical gradient captured by PC1. Together, PC1 and PC2 account for 90.38% of the total variance, indicating that the first two axes effectively summarize the dominant hydrocarbon-related variability within the dataset.

Vectors corresponding to São Francisco (SF) samples extend predominantly toward the positive side of PC1, reflecting their higher TPH and TOC values. In particular, SF3

exhibits the longest vector magnitude, indicating the greatest deviation from the dataset centroid and reinforcing its distinct geochemical signature. SF2 and SF1 also project toward positive PC1 values, although with different orientations along PC2, suggesting intra-sector heterogeneity.

In contrast, Baixa Fria (BF) samples project toward the negative side of PC1 and display shorter vector magnitudes overall, indicating lower hydrocarbon loads and greater geochemical similarity among these sites. BF1, BF2, and BF3 cluster closely in ordination space, whereas BF4 shows moderate displacement along PC2, suggesting secondary variability within the BF sector.

Although no formal inferential tests were applied to compare groups, the convergence of evidence across independent analytical approaches strengthens the interpretation of a structured environmental gradient. Consistent spatial patterns were identified through univariate TPH comparisons, statistically significant TOC–TPH correlation ($r = 0.864$, $p = 0.012$), grain-size characterization, and multivariate ordination (PCA). This coherence indicates that differences between SF and BF sediments reflect integrated geochemical controls rather than isolated variables.

Importantly, the spatial structuring observed in bacterial community composition mirrors the geochemical heterogeneity identified in the sediments. Sites characterized by elevated TOC and TPH values occupy distinct positions in multivariate space and exhibit differentiated taxonomic profiles, whereas carbon-poor, low-TPH sites cluster more tightly. While the present dataset does not allow causal inference, the concordance between geochemical gradients and community structure suggests that sedimentary carbon dynamics and hydrocarbon distribution are key factors associated with bacterial assemblage variability.

Taken together, the integration of taxonomic, geochemical, and sedimentological data reveals clear spatial heterogeneity within the mangrove sediments of São Francisco do Conde. The combined use of correlation analysis and multivariate ordination provides a coherent framework for interpreting sediment variability under chronic petroleum influence while avoiding overextension into functional claims. These findings establish a robust descriptive baseline for future studies incorporating metagenomic, enzymatic, or long-term monitoring approaches.

4 CONCLUSIONS

The present study demonstrates that spatial variability in bacterial community structure within mangrove sediments from São Francisco do Conde is strongly associated with geochemical heterogeneity, particularly differences in total organic carbon (TOC) and total petroleum hydrocarbon (TPH) concentrations. The statistically significant positive correlation between TOC and TPH ($r = 0.864$, $p = 0.012$, $n = 7$) supports the interpretation that organic carbon content exerts a primary control on hydrocarbon retention in these sediments.

Multivariate ordination further revealed a structured environmental gradient separating São Francisco and Baixa Fria sites along hydrocarbon-related axes, with São Francisco samples exhibiting higher TPH loads and greater geochemical dispersion. In contrast, Baixa Fria sediments displayed lower hydrocarbon concentrations and tighter clustering in ordination space, indicating comparatively homogeneous geochemical conditions.

Taxonomic profiling identified the predominance of bacterial genera frequently reported in organic-rich and petroleum-influenced coastal sediments, including Marinobacter, Acinetobacter, Bacillus, and Anaerolinea. While functional inferences remain speculative in the absence of metabolic or gene-based analyses, the concordance between geochemical gradients and community structuring suggests that sedimentary carbon dynamics and hydrocarbon distribution are important factors associated with bacterial assemblage variability.

The predominance of fine-grained fractions (silt and clay) characterizes low-energy depositional environments that favor organic matter accumulation and hydrophobic contaminant stabilization. However, correlation analyses indicate that organic carbon content exerts a stronger influence on hydrocarbon distribution than sediment texture alone.

Overall, the integration of high-throughput 16S rRNA gene sequencing with geochemical and sedimentological analyses provides a coherent framework for interpreting sediment–microbe associations in chronically oil-influenced tropical mangrove systems. Although causal relationships cannot be established from the present dataset, the results establish a robust descriptive baseline for future investigations incorporating functional genomics, process-based measurements, and long-term environmental monitoring.

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