



An Assessment of the Filtration and Adsorption Characteristics of Indigenous Clay for Brackish Water Purification

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Abstract

The escalating global water crisis necessitates sustainable and cost-effective solutions for brackish water purification. This study characterises an indigenous clay sample to evaluate its potential as an adsorbent and a multi-functional bio-filter for brackish water treatment. An advanced analytical technique was employed, including X-ray Diffraction (XRD), X-ray Fluorescence (XRF) elemental analysis, Fourier-transform infrared spectroscopy (FTIR), and Brunauer–Emmett–Teller (BET) surface area and porosity measurements. The XRD results showed that the clay examined is a complex mineralogical assemblage, predominantly composed of quartz (49.0%), orthoclase (16.4%), chlorite (14.0%), muscovite (10.0%), albite (9.3%), and illite (1.36%). Similarly, XRF elemental analysis corroborated a silicate-rich composition (46.3% SiO₂, 38.2% Al₂O₃). In addition, FTIR spectroscopy provided a chemical fingerprint, confirming the silicate framework, indicating the likely presence of palygorskite as well as organic matter, adsorbed water, and potential iron oxyhydroxides and gypsum. Essentially, BET analysis demonstrated an exceptionally high multipoint surface area of 389.4 m²/g, coupled with a dual-scale porous structure dominated by micropores and small mesopores of 1.8-6.5nm average pore diameters and suggests a Type IV isotherm with an H1 hysteresis loop. These properties illustrate that indigenous clay is excellent for biofiltration, high in quartz and minerals supporting adsorption and ion exchange capabilities. The surface area is suitable for creating an optimal environment for microbial colonisation and biofilm development, thereby enhancing the biological degradation of pollutants. Overall, the clay under consideration is highly effective at removing suspended solids, heavy metals, and biodegradable pollutants.

Keywords: Filtration; adsorption; biofiltration; brackish water; salinity

1. Introduction

Brackish water is polluted and not fit for human consumption if not treated. The exploration of non-conventional water resources and the development of sustainable purification technologies have become increasingly vital. Brackish water, characterised by a salinity level intermediate between freshwater and seawater (typically ranging from 0.5 to 30 practical salinity units (PSU)), represents a substantial water reserve, particularly prevalent in coastal zones and arid or semiarid landscapes of the Niger Delta region (Kim et al., 2024). Additionally, brackish water is typically defined as water having a salinity concentration between that of freshwater and seawater. Resistivity measurements conducted in Lekki, Lagos State, Nigeria, have indicated brackish water with values ranging from 80 to 120Ωm (Adepelumi et al., 2009). In the Lower Niger Delta, salinity levels have been recorded with a mean of 6269.95 ± 67.25 mg/L. The salinity tolerance of various aquatic species, as documented in research, ranges from 0 to 35 parts per thousand (ppt), providing a benchmark for acceptable levels in treated water depending on its intended use (Venâncio et al., 2022). Brackish water in the Niger Delta originates from several primary sources, including increasing saltwater intrusion into coastal aquifers, a phenomenon exacerbated by unplanned and excessive groundwater abstraction (Edet, 2022). In Nigeria, particularly within the intricate deltaic ecosystems of the Niger Delta region, brackish water bodies are a common feature due to the confluence of freshwater rivers and the influence of the Atlantic Ocean (Oyegun et al., 2023). The Delta South Senatorial District, with its extensive network of creeks, estuaries, and coastal communities, is characterised by the significant presence of brackish water resources. However, the utility of these water sources is often limited by elevated salinity levels and the potential co-occurrence of other contaminants, including suspended solids, organic matter, microbial pathogens, and heavy metals originating from both natural geological processes and anthropogenic activities such as oil exploration and agricultural runoff (Da'ana et al., 2021; Wang et al., 2025). Consequently, effective and affordable treatment methods are essential to harness the potential of these brackish water resources for various beneficial uses, including domestic consumption, agriculture, and industrial applications.

Conventional water treatment plants capable of achieving high levels of purification often entail significant capital investment, high operational costs associated with energy and chemical inputs, and the generation of concentrated waste streams that require careful management (Chalaris et al., 2023). Nonetheless, these limitations can pose significant barriers to their widespread adoption, especially in resource-constrained communities and developing regions. This necessitates a focused effort on the characterization of indigenous clay as a biofilter for brackish water. The utilization of locally sourced materials for water treatment has gained considerable traction in recent years. Among these

materials, clay minerals have emerged as promising candidates due to their natural abundance, low cost, and inherent physicochemical properties that facilitate the removal of a wide range of pollutants (Shiferraw et al., Agbale, et al., 2024). The unique layered structure, high surface area, and significant cation exchange capacity of clay minerals enable them to effectively adsorb groups metals, organic compounds, and particulate matter from aqueous solutions. Functional groups such as Al-OH, and Si-OH provide active sites for the binding of cations, Groups such as Fe-OH increase positive sites which attract anionic impurities such as the chlorides and sulphates contained in the respective salts found in the brackish water. Additionally, the mesoporous structures of some clays contribute to an extensive surface area and pore networks that physically trap suspended solids and microorganisms, making them a highly effective filter medium.

Biofiltration, a process that leverages the metabolic activities of microorganisms immobilised on a filter medium, presents a biologically driven and potentially sustainable approach to water purification (Kamalesh et al., Agbale, et al., 2025). The microbial community within the biofilm can degrade organic pollutants, remove nutrients, and contribute to the inactivation of pathogens (Bala, et al., 2022). Integrating the adsorptive capabilities of clay with the biological treatment potential of a biofilm in a hybrid bio-filter system could create a synergistic effect, enhancing the overall efficiency of brackish water purification by simultaneously addressing both chemical and biological contaminants (Unuabonah et al., 2014). The clay matrix can provide a stable and protective environment for microbial colonization and activity, while the microorganisms contribute to the breakdown of complex pollutants that may not be effectively removed by physical adsorption alone (Fomina and Skorocho, 2020). This research focuses on the analysis of indigenous lay samples for the determination of their effectiveness in the integrated treatment of brackish water through filtration and adsorption.

2. Materials and Methods

The clay material used was obtained from Egbokodo Itsekiri, Warri in Delta State, Nigeria (5°31'2.53" N 5°45'0.22" E). Prior to the analytical procedures on the clay sample, it was thoroughly washed in distilled water and dried in a dryer at 100 °C for 24 hours. It was then passed through a stack of screens for fractionation into different sizes, however about 95% by mass of the clay passed through the 100 mesh screen (100 μm) into the 120 mesh screen (150 μm). The functional groups and molecular binding forms present in the sample were analysed using the Shimadzu Fourier Transform Spectrophotometer (-FTIR 8400 S) and the data were taken on K-Br pellets with a resolution of 4 cm⁻¹ in the range of 450 cm⁻¹ to 4000 cm⁻¹. A powder X-ray diffractometer (Rigaku MiniFlex X-ray Diffractometer), equipped with a Cu-Kα radiation source, was utilised to identify crystalline phases in the clay sample at diffraction angles (2-Theta).

Furthermore, a Thermo Fisher X-ray Fluorescence (XRF) Spectrometer was deployed for elemental composition as well as quantifying both major and trace elements. The Brunauer–Emmett–Teller (A Quantachrome NOVA4200e instrument) surface analysis, N₂ adsorption-desorption was performed at 77K, while the sample was degassed for 12 h at 200 °C before the adsorption-desorption measurement.

3. Results and Discussion

3.1. Functional Group Analysis Result of Clay Sample

The results of the Fourier transform Infra-red spectroscopy (FTIR) of indigenous clay are shown in Figure 1.

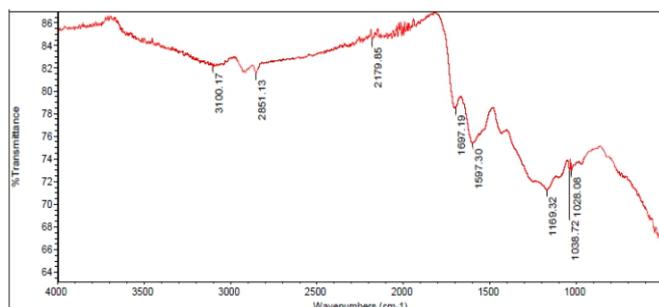


Figure 1: FTIR of Clay

Clay sample was found to have a broad OH band at ~3100 cm⁻¹, and the intense Si–O stretches (~1038 cm⁻¹) confirm the presence of layered aluminosilicate minerals, likely kaolinite or montmorillonite. Similarly, quartz impurity displayed a sharp Si–O–Si stretch with matched quartz signatures, suggesting natural silica contamination. In addition, carbonate presence was found at 2179 cm⁻¹ band corresponding to carbonate overtones, indicating calcite or dolomite impurities. Organic matter was noticed at 2851 cm⁻¹ (C–H) and 1697 cm⁻¹ (C=O) bands suggesting trace humic substances or other organic residues in the clay. Essentially, moisture content peaks at 3100 cm⁻¹ and 1597 cm⁻¹, confirming bound and adsorbed water, typical of hydrated clays. Overall, the FTIR results show that the clay sample is heterogeneous, consisting of primary mineral i.e., hydrated aluminosilicate (kaolinite/montmorillonite), while secondary mineral impurities like quartz and carbonates (calcite/dolomite) were found with trace organic content (humic matter). The presence of OH- facilitates the adsorption of positively charged ions and other polar organic. They also increase the hydrophilic nature of the clay, thereby promoting wetting and the ease at which pollutants are moved to the pores (Cardona et al., 2022). The presence of Si-O-Si implies that the sample is negatively charged. This, in turn, has been found to increase the surface area and cation exchange capacity. These properties have been found to greatly enhance the adsorption of positively charged metals, such as Na, Pb, and Mg, from solution with ease (Madejová, 2003). In the study conducted by Baskaran & Saravanane, (2020) on the partial treatment of seawater using montmorillonite, 90% of Na ions were removed after the adsorption treatment on montmorillonite. Studies conducted by Gorakhki & Barether (2015) and Trach et al (2022) showed that kaolin was highly effective for the treatment of brackish water.

3.2 Determination of the Crystalline Structure of Clay Sample

The X-ray Diffraction (XRD) analysis of the clay sample is shown in Figure 2 and provides a precise quantitative and qualitative identification of its crystalline mineral phases, offering critical insights into its potential application as a bio-filter for brackish water purification.

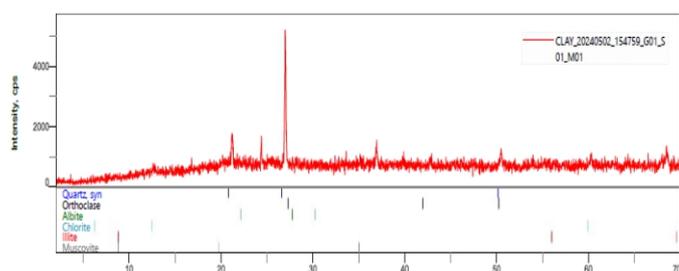


Figure 2: X-ray Diffraction of clay sample

The sample is a complex mixture, with a significant proportion of non-clay minerals alongside various clay types. XRD results indicate the following composition: quartz (49.0%), orthoclase (16.4%), chlorite (14.0%), muscovite (10.0%), albite (9.3%) and illite (1.36%). The suitability of this mineral assemblage as a bio-filter for brackish water purification hinges on the collective

properties of its constituent minerals, particularly their physical filtration capabilities, adsorption capacities, ion exchange characteristics, and ability to support microbial growth (see Figure 3).

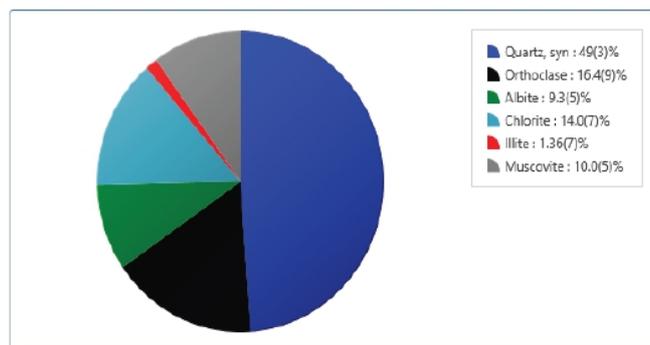


Figure 3: Clay Composition

Quartz (49.0%), being the most abundant mineral, serves as the primary physical filtration medium (Khan, Ajmal, Hussain, & Rahman, 2025). Its high hardness, wear resistance, and stable chemical properties make it an excellent choice for removing suspended solids, organic matter, colloidal particles, and even some microorganisms from water (Annan, et al., 2018). The pores between quartz grains are sufficiently small to effectively trap many impurities without reacting with the water itself (Ihekwe, et al., 2020). This physical barrier is a fundamental component of any filtration system. Nonetheless, Chlorite (14.0%) and Illite (1.36%) are crucial for the adsorption and ion exchange. Clay minerals generally possess large surface areas and significant cation exchange capacities (CEC) due to negative charges resulting from isomorphous substitutions within their crystal structures (Perelomov, et al., 2025). This enables them to effectively adsorb positively charged contaminants, including metal ions and various dyes present in wastewater, through cation exchange mechanisms (Sarkar et al., 2023). Muscovite (10.0%) is a mica mineral; muscovite also exhibits significant water adsorption capabilities.

Accordingly, water adsorption on muscovite occurs in distinct stages, with a strongly bound first layer of water molecules occupying ditrigonal cavities (Koishi et al., 2022). This property can contribute to the overall hydration and retention capacity of the filter medium, potentially influencing the microenvironment for biofilm development. The Orthoclase (16.4%) and Albite (9.3%) are feldspar minerals and primarily contribute to the structural integrity and physical framework of the filter medium. While less active in direct adsorption or ion exchange compared to the clay minerals, their presence ensures the stability and porosity of the filter bed. Water can enter orthoclase crystals under pressure, suggesting some interaction with water and potential for micropore formation, which could indirectly support filtration or microbial habitats (Diaz-Mateus et al., 2024)

3.3 XRF Analysis Result of Clay Sample

The metallic oxide composition of the clay sample is shown in Table 1. The silica to Alumina ratio was found to be 1.21, this confirms the presence of rich kaolinite minerals, as confirmed by studies conducted by Kgabi and Ambushe (2023), Kumar and Lingfa (2020) and Omang et al (2019). Kaolinite is effective in the adsorption of both heavy metals and organics, either in its pristine form, activated or as a constituent of a composite. In the study by Mustapha et al (Mustapha, et al., 2019) on the treatment of wastewater on kaolin, the results showed that equilibrium adsorption efficiencies were obtained as follows: sulphate (71.11 %), COD (72.83 %), chloride (66.75 %), total alkalinity (85.91 %) and BOD (82.65 %) at contact times of 10, 15 and 20 min.

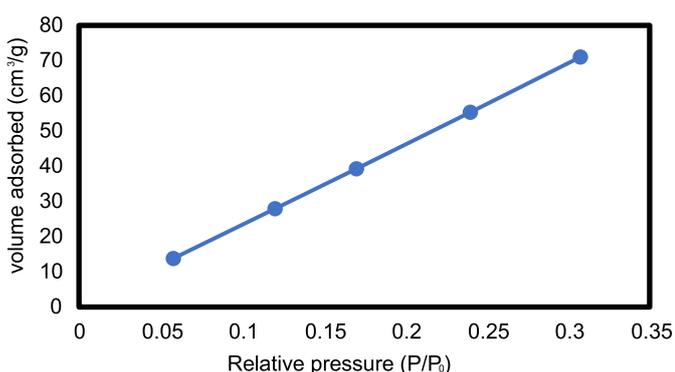
More so, the equilibrium adsorption efficiencies for the removal of Cr, Cd and Zn from the wastewater were 53.01 %, 59.34 % and 66.03 %, respectively, based on 15 min contact times. Additionally, Kaolin was effective in the removal of sulphate ions from wastewater in the work done by Hudaib et al (2019). Other metallic oxides found in the sample include CaO (6.06%), TiO₂ (5.28%), and Fe₂O₃ (1.95%). ZrO₂ (0.53%), Chlorates (0.84%). The high concentration of CaCO₃ is likely to facilitate the removal of heavy metals and act as a neutralising agent and coagulating aid, which reacts with some impurities to form sediments that can easily be removed by filtration (Wang, Wang, Shammass, & Hahn, 2021). The presence of Fe₂O₃ may likely enhance the cation exchange capacity of the clay, thereby making the clay more effective for the removal of highly electropositive metals such as Na, K, and Mg, which constitute the salts present in the water (Navratil, 1999). TiO₂ exhibits photocatalytic and antimicrobial properties, contributing to the breakdown of organic pollutants and suppression of microbial growth (Shang, Bu, & Song, 2022).

Table 1: Oxide content of the Clay

Oxide	Composition (%)
SiO ₂	46.30
Al ₂ O ₃	38.24
CaO	6.06
TiO ₂	5.28
Fe ₂ O ₃	1.95
ZrO ₂	0.53
Cl	0.84
Others (CuO, ZnO, MnO ₂)	< 1

3.4 Determination of Surface Area, Pore Size and Pore Volume

The nitrogen adsorption isotherm of the clay sample shown in Figure 4 exhibits the characteristic features of a Type IV isotherm, which is typical of mesoporous materials. As shown by the isotherm data, the volume of nitrogen adsorbed increases gradually at low relative pressures ($P/P_0 < 0.1$), indicating initial monolayer-multilayer adsorption on the clay surface. This region corresponds to the adsorption of nitrogen molecules onto the external surface and the walls of the pores. The textural properties of the clay are shown in Table 2. The Multipoint BET specific surface area of 389.449 m²/g is a significantly high value for a natural clay sample. From previous studies, the specific surface areas of some natural clay samples are 10-30 m²/g for kaolin (Li et al., 2015; Shu et al., 2016; Kgabi and Ambushe, 2023), 50-1500 m²/g for bentonite (Suárez et al., 2022; Gandhi et al., 2022), and between 600 – 800 m²/g for montmorillonite (Al Kausor et al., 2022; Fan et al., 2023; Dai et al., 2023). This high surface area is a direct consequence of the sample's mineralogical composition, particularly the presence of clay minerals identified in previous analyses (ELsayed, et al., 2025). The Langmuir surface area (9051.795 m²/g) is considerably higher than the BET value. This is common for materials with heterogeneous surfaces or significant microporosity, as the Langmuir model assumes ideal monolayer adsorption on all sites, including those where multilayer adsorption might occur (Staudt, et al., 2024). The high Langmuir value suggests strong adsorbate-surface interactions.

Figure 4: N₂ Adsorption Isotherm of the clay sampleTable 2: Textural Properties of clay from the N₂ adsorption analysis (BET analysis)

Method	Surface Area (m ² /g)	Pore Volume (cm ³ /g)	Pore Size / Diameter (nm)
Multi-point BET	389.45	–	–
BJH (adsorption)	404.11	0.199	2.09
DA (micropores)	–	0.346	3.00
DFT (slit-pore)	83.12	0.101	2.65

The Multi-point BE area of (389.45 m²/g), suggests that a substantial portion of the total surface area originates from micropores (pores < 2 nm). This is further supported by the relatively low constant, which can sometimes be observed in microporous materials. The various pore volume and pore diameter values indicate a material with a complex pore network, primarily dominated by micropores (pores < 2 nm) and small mesopores (2-50 nm). The DA Micropore volume (0.346 cm³/g) and DR Micropore volume (0.138 cm³/g) confirm the significant presence of micropores. The mode pore diameters from different models (DFT: 2.65 nm; BJH: 2.09 nm; DA: 3.000 nm) consistently fall within the micropore to small mesopore range. This indicates a very fine pore structure. This pore size distribution is highly characteristic of clay minerals, which form layered structures with interparticle voids and internal channels (as in palygorskite), leading to a high proportion of fine pores (Seifi et al., 2023). Similarly, the pore volume of ~0.20–0.35 cm³ g⁻¹ is significantly higher than that of conventional kaolinite (typically <0.05 cm³ g⁻¹) and approaches that of engineered adsorbents used in water purification. This enhanced porosity is

likely due to a combination of carbonate dissolution, iron-oxide surface roughening, and structural defects, which generate additional micropores and mesopores. Compared with bentonite, which has moderate surface area (60–150 m² g⁻¹) but poor chemical stability in saline environments, this kaolinite-based clay provides a much higher surface area while retaining structural stability in brackish water.

4. Conclusion

The XRD established a multi-mineral assemblage, predominantly comprising quartz (49.0%), orthoclase (16.4%), chlorite (14.0%), muscovite (10.0%), albite (9.3%), and illite (1.36%). This mineralogical diversity is fundamental to the clay's multifaceted filtration capabilities. The XRF results of analysis largely corroborated the XRD, revealing high concentrations of silicon (Si) and aluminum (Al), alongside notable levels of calcium (Ca) and iron (Fe). These elements are integral to the structural integrity and potential reactive sites within the filter medium. Conversely, the FTIR spectroscopy provided a detailed chemical fingerprint, confirming the presence of a silicate through Si-O-Si stretching vibrations (1038.72 cm⁻¹ and 1028.08 cm⁻¹) and indicates the likely presence of palygorskite as well as organic matter (C-H and C=O stretching at 2851.13 cm⁻¹ and 1697.19 cm⁻¹, respectively) with water adsorption (H-O-H bending at 1597.30 cm⁻¹), and potential iron oxyhydroxides (goethite at 3100.17 cm⁻¹). These functional groups are pivotal for adsorption mechanisms and foster biological activity within the filter. Essentially, the BET surface area and porosity analysis showed exceptionally favourable physical characteristics with samples exhibiting a high multipoint surface area of 389.449 m²/g, significantly exceeding typical values for many natural clays. This expansive surface area is complemented by a pore structure predominantly characterised by micropores (pores < 2 nm) and small mesopores (2-50 nm), as indicated by various pore size models (e.g., HK: 1.847 nm, BJH: 2.088 nm, DFT: 2.647 nm, DA: 3.000 nm, DR: 6.500 nm). The nitrogen adsorption isotherm, exhibiting an initial steep uptake, is consistent with a Type I or Type IV classification, signifying substantial micropore filling and potential mesopore condensation. This intricate pore network is paramount for efficient mass transfer and adsorption processes. This multi-modal purification mechanism—integrating physical entrapment, chemical adsorption, and biological processes—underscores the clay's potential to effectively remove suspended solids, heavy metals, and biodegradable organic matter from brackish water.

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