Evaluation of Palm Oil (Elaeis guineensis) by-products as bioadsorbents for the removal of nitrites, phosphates, and sulfates in domestic wastewater

Evaluación de subproductos de aceite de palma (Elaeis guineensis) como bioadsorbentes para la eliminación de nitritos, fosfatos y sulfatos en aguas residuales domésticas

Avaliação de subprodutos de óleo de palma (Elaeis guineensis) como bioadsorventes para eliminação de nitritos, fosfatos e sulfatos em águas residuais domésticas

Bleydy Ortega-Vergara[a], Hugo Hernández-Palma[b], Alcindo Neckel[c], Andrea Liliana Moreno-Ríos[d]

a Servicio Nacional de Aprendizaje, SENA, Centro Agropecuario y de Biotecnologia El Porvenir. Km 47 vía Tierralta, Corregimiento Santa Isabel, Córdoba (Colombia). Email: bortegav@sena.edu.co.

b Corporación Universitaria Iberoamericana, Facultad de Ingeniería, Programa Ing industrial, Calle 67 # 5-27. Bogotá (Colombia). hugo.hernandez@ibero.edu.co. ORCID: https://orcid.org/0000-0002-3873-0530. jonny.plazas@ibero.edu.co. https://orcid.org/0000-0002-4342-6699.

c Posgraduate Program in Architecture and Urbanism, Atitus Educação, R. Sen. Pinheiro, 304 - Vila Rodrigues, Passo Fundo - RS, 99070-220, Rio Grande do Sul, Brasil. Email: alcindo.neckel@atitus.edu.br ORCID: https://orcid.org/0000-0001-5435-3096

d Universidad de Cartagena, Facultad de Química Farmacéutica, Campus Zaragocilla, Calle 30 #39 B-192, Cartagena, Bolivar, (Colombia). morenoriosandrea@gmail.com ORCID: https://orcid.org/0000-0002-5454-6784.

**Corresponding author: Andrea Liliana Moreno Ríos, email: morenoriosandrea@gmail.co*

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Abstract

The growing global concern for environmental sustainability has driven the search for efficient solutions in wastewater treatment. This study evaluated the potential of palm oil (*Elaeis guineensis*) by-products, specifically the shell and fiber, as adsorbents for removing nitrites, phosphates, and sulfates from domestic wastewater. The nutrient removal efficiency was determined using spectrophotometry. The effect of operational variables such as the type and amount of bioadsorbent material and contact time on the removal efficiency of these pollutants was evaluated. The results indicated that the fiber exhibited a high adsorption capacity, removing 95.55% of nitrites, 87.50% of sulfates, and 26.2% of phosphates. These findings suggest that palm oil by-products offer a cost-effective and sustainable solution for wastewater treatment, particularly in countries such as Colombia, contributing to the achievement of the United Nations Sustainable Development Goals (SDGs) for 2030, specifically SDG 6 and SDG 12, target 6.3, which focus on improving water quality by reducing pollution and minimizing the release of hazardous substances.

Keywords: Bioadsorbents, pollutants, wastewater, by-products, shell, fiber.

Resumen

La creciente preocupación mundial por la sostenibilidad ambiental ha impulsado la búsqueda de soluciones eficientes en el tratamiento de aguas residuales. En este estudio se evaluó el potencial de los subproductos del aceite de palma (*Elaeis guineensis*), específicamente la cáscara y la fibra, como adsorbentes para la remoción de nitritos, fosfatos y sulfatos de las aguas residuales domésticas. La eficiencia de remoción de nutrientes se determinó mediante espectrofotometría. Se evaluó el efecto de variables operativas como el tipo y la cantidad de material bioadsorbente y el tiempo de contacto sobre la eficiencia de remoción de estos contaminantes. Los resultados indicaron que la fibra exhibió una alta capacidad de adsorción, removiendo el 95.55% de nitritos, el 87.50% de sulfatos y 26.2% de fosfatos. Estos hallazgos sugieren que los subproductos del aceite de palma ofrecen una solución rentable y sostenible para el tratamiento de aguas residuales, particularmente en países como Colombia, contribuyendo al logro de los Objetivos de Desarrollo Sostenible (ODS) de las Naciones Unidas para 2030, específicamente el ODS 6 y el ODS 12, meta 6.3, que se centran en mejorar la calidad del agua reduciendo la contaminación y minimizando la liberación de sustancias peligrosas.

Palabras clave: Bioadsorbentes, contaminantes, aguas residuales, subproductos, concha, fibra.

Resumo

A crescente preocupação global com a sustentabilidade ambiental tem impulsionado a busca por soluções eficientes no tratamento de águas residuais. Este estudo avaliou o potencial dos subprodutos do óleo de palma (*Elaeis guineensis*), especificamente a casca e a fibra, como adsorventes para remoção de nitritos, fosfatos e sulfatos de águas residuais domésticas. A eficiência de remoção de nutrientes foi determinada usando espectrofotometria. O efeito de variáveis operacionais, como o tipo e a quantidade de material bioadsorvente e o tempo de contato na eficiência de remoção desses poluentes, foi avaliado. Os resultados indicaram que a fibra apresentou alta capacidade de adsorção, removendo 95.55% dos nitritos, 87.50% dos sulfatos e 26.2% dos fosfatos. Essas descobertas sugerem que os subprodutos do óleo de palma oferecem uma solução econômica e sustentável para o tratamento de águas residuais, especialmente em países como a Colômbia, contribuindo para a consecução dos Objetivos de Desenvolvimento Sustentável (ODS) das Nações Unidas para 2030, especificamente o ODS 6 e o ODS 12, meta 6.3, que se concentram na melhoria da qualidade da água, reduzindo a poluição e minimizando a liberação de substâncias perigosas.

Palavras-chave: Bioadsorventes, poluentes, águas residuais, subprodutos, conchas, fibras.

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1. Introduction

Water is essential for life, public health, and environmental sustainability (Dalmora et al., 2022). However, the inadequate treatment of wastewater remains a serious global issue. Approximately 80% of wastewater is discharged into the environment without proper treatment (World Bank, 2020). This situation highlights the need to strengthen wastewater infrastructure and raise public awareness about the conservation and protection of water resources (Aldana, 2020).

Untreated domestic wastewater has detrimental effects on aquatic ecosystems and human health. Key impacts include decreased dissolved oxygen levels, the presence of pathogens, and eutrophication caused by excess nutrients such as nitrates, nitrites, phosphates, and sulfates (Linhares, 2017). Nitrites signal fecal contamination and pose direct health risks (León et al., 2023), while phosphates and sulfates promote eutrophication, threatening biodiversity and causing economic losses (Chuquimboques et al., 2019; Checmapocco and Hoyos, 2022). Effective removal of these nutrients is vital to protect water quality and maintain ecosystem balance (Oviedo et al., 2023). Additionally, parameters such as pH and total dissolved solids influence microbial activity and contaminant solubility, reinforcing the importance of comprehensive treatment strategies (Rodríguez et al., 2022; Azabache and Quispe, 2020).

Proper wastewater treatment not only protects ecosystems but also enables water reuse in agriculture and industry, supporting energy generation and soil improvement. Treatment methods range from basic filtration to advanced adsorption and chemical processes, all aiming to reduce contaminant loads and promote water sustainability (Barbosa et al., 2021). Given that nearly 36% of the world's population resides in water-stressed regions, integrating wastewater reuse into mitigation strategies is critical (Aldana, 2020).

Among various techniques, adsorption has emerged as a sustainable and cost-effective method for removing contaminants. Adsorbent materials derived from waste can eliminate both organic and inorganic pollutants, including heavy metals and persistent compounds harmful to ecosystems and human health (Castillo, 2023; Georgin et al., 2023; Coronado-Herrera et al., 2023). Conventional adsorbents like activated carbon (Condor and Maza, 2020; Torres et al., 2020; Orellano, 2024), zeolites (Barbosa et al., 2021; Ferreira, 2021; Castro et al., 2022), molecular sieves (Mamani, 2023; Gómez and Rugeles, 2023), hydrogels (Burciaga et al., 2020; Castañeda & Álvarez, 2024), and silica gel (Lateef et al., 2022) are effective but often costly and not always reusable. In contrast, bioadsorbents—non-conventional materials derived from agricultural waste like coconut shells, coffee grounds, and banana peels—offer affordable, abundant, and eco-friendly alternatives (Duany et al., 2022; Valladares et al., 2024). Their performance, however, depends on prior treatment and the nature of the contaminant.

Among agricultural by-products, palm oil residues stand out for their adsorption potential (Acevedo et al., 2021), especially in urban areas affected by diverse pollution sources like agriculture and domestic or industrial discharges (Téllez et al., 2023). Colombia is a major palm oil producer, with over 595,000 hectares under cultivation and an annual output of 1.7 million tons in 2021 (Fedepalma, 2024). This industry generates large quantities of by-products such as shell and fiber, which exhibit physicochemical characteristics favorable for wastewater treatment (Moreno, 2013; Oyehan et al., 2022; Siddiqui et al., 2024).

Among agro-industrial wastes with potential as bioadsorbents, by-products of palm oil have received considerable attention (Acevedo et al., 2021). This interest is particularly relevant in urban areas affected by multiple sources of pollution, such as agriculture and domestic and industrial discharges, which degrade water quality (Téllez et al., 2023). In Colombia, palm oil is one of the primary sources of vegetable oil, with a cultivated area of 595,722 hectares and an annual production of 1,747,000 tons in 2021 (Fedepalma, 2024). The processing of palm oil generates by-products such as shell and fiber, which have physical-chemical properties suitable for use as adsorbents in the purification of wastewater (Moreno, 2013; Oyehan et al., 2022; Siddiqui et al., 2024).

Palm shell and fiber have shown promise as bioadsorbents. The shell, commonly used as fuel or filler, also treats wastewater in domestic and industrial settings (Acevedo et al., 2021; Pulingam et al., 2022). The fiber has a high surface area and is rich in lignin, cellulose, hemicellulose, and pectin, facilitating adsorption through physical and chemical interactions (Martinez and Naranjo, 2021; Moreno, 2020; Cavazos, 2021). Thermochemical processing further enhances their adsorption efficiency and supports sustainable agro-industrial waste management (Cavazos, 2021; Alvarez, 2020; Oyehan et al., 2022; Siddiqui et al., 2024).

This study contributes to the achievement of the United Nations Sustainable Development Goals (SDGs), particularly SDG 6 and SDG 12. Target 6.3 focuses on improving water quality by reducing pollution and minimizing hazardous discharges, while Target 12.5 promotes waste reduction through prevention, recycling, and reuse (SDG, 2023).

The objective of this study is to evaluate the efficiency of palm oil by-products—specifically shell and fiber—as adsorbents for removing nitrites, phosphates, and sulfates from domestic wastewater. The study also assesses their technical and environmental feasibility in a local context, generating valuable insights for the treatment of wastewater at the SENA El Porvenir Training Center, with potential applicability in other regions of Colombia and globally.

2. Materials and methods

2.1. Preparation of bioadsorbent materials from the shell and fiber of the palm oil

Samples of palm oil by-products (shell and fiber) were provided by the company Sinú, a subsidiary of the Oleoflores Business Group. These materials were collected directly from the processing plant. The shell and fiber were manually separated into 500 g portions and stored in sealed plastic bags for transport to the Environmental Research Center (CITA) laboratory at Universidad de la Costa, where the preparation process was conducted.

Initially, each sample was washed with distilled water to remove impurities and then air-dried at room temperature under sunlight until completely dry. The dried samples were then crushed and ground using a standard hand mill. Subsequently, the material underwent thermal treatment in a muffle furnace with progressive heating at 30-minute intervals: starting at 100°C, increasing to 150°C, and finally reaching 200°C. After cooling, the samples were sieved sequentially using 20 mm and 100 mm mesh sieves to obtainuniform particle sizes.

Figure 1. Samples of shell and fiber.

2.2. Evaluation of bioadsorbents in the removal of nutrients in domestic wastewater

The adsorption capacity of palm oil shell and fiber was evaluated using domestic wastewater under laboratory conditions. The experiments were conducted in a batch system with magnetic stirring at 300 rpm and room temperature for a duration of 4 hours. Each test was carried out in a 1000 ml beaker containing 400 ml of water (Díaz and Rodelo, 2019). Two controls were used: distilled water (Control-1) and untreated domestic wastewater (Control-2). Fourteen (14) treatments were performed, as summarized in Table 1.

Table 1. Treatments carried out to evaluate the adsorption capacity of bioadsorbents.

Water sample	Bioadsorbent material	Treatment	Bioadsorbent concentration g l-1
Distilled Water (DW)	None	DW	0
	Shell (S)	DWS-1	6
		DWS-2	12
		DWS-3	18
	Fiber (F)	DWF-1	6
		DWF-2	12
		DWF-3	18

	None	WW	0
		WWS-1	6
	Shell (S)	WWS-2	12
Wastewater (WW)		WWS-3	18
		WWF-1	6
	Fiber (F)	WWF-2	12
		WWF-3	18

The selected bioadsorbent concentrations (6, 12, and 18 g l^{-1}) were based on preliminary trials and literature reports, which indicated that this range is suitable for assessing dose-dependent adsorption behavior in similar systems (Díaz, and Rodelo, 2019; Moreno, 2013). This gradient allowed evaluation of the effect of dosage on nutrient removal and helped determine an optimal balance between removal efficiency and material usage. The selection also considered practical feasibility for small-scale treatment applications and potential adsorption saturation thresholds based on prior evidence using agro-industrial residues.

The wastewater (20 l) was collected from the El Porvenir Agricultural and Biotechnology Center, part of the National Learning Service (SENA), located in Santa Isabel, Córdoba, Colombia (Coordinates: N 8° 34′ 18.64″; W 75° 56′ 49″). The procedure followed the guidelines in the IDEAM monitoring manual for discharges, surface water, and groundwater (Decree 1076 of 2015; IDEAM, 2010).

The adsorption tests were conducted over 4 hours, with 300 ml samples taken at 0, 2, and 4 hours. The samples collected at 2 and 4 hours were centrifuged at 3000 rpm for 15 minutes at 25°C to separate the bioadsorbent particles. All samples were analyzed for physicochemical parameters listed in Tables 2 and 3, following the procedures outlined in the Standard Methods for the Examination of Water and Wastewater, 23rd edition (Baird et al., 2017).

Table 2. Parameters evaluated in the initial wastewater sample.

Parameters	Unit	Method	Equipment
pH	Valor	SM 4500-H B.Ed 23 rd-2017.	Multiparameter EcoSense Ph100 A
Temperature	°C	SM 2550-B. Ed 23-2017	
Conductivity	µS cm-1	SM 2510- B.Ed 23rd-2017.	
Salinity	g l-1	SM 2520- B.Ed 23rd-2017.	
Nitrite (NO2)	mg l-1	SM 4500- NO2- B.Ed 23rd-2017.	Photometer EcoSence series 9300
Phosphate (PO4)	mg l-1	SM 4500- PO4- B.Ed 23rd-2017.	
Sulfate (SO4)	mg l-1	SM 4500- SO4- B.Ed 23rd-2017.	

The results show the average data for each parameter analyzed and the removal percentage for the nutrients (nitrites, phosphates, and sulfates). Equation 1 was used to calculate the percentage of removal.

$$\% \text{ Removal} = \frac{\text{Initial concentration} - \text{End concentration}}{\text{Initial concentration}} \times 100 \text{ Equation 1}$$

3. Results and discussions

Nutrient removal assessment

The physicochemical parameters of distilled and wastewater samples used in the experiments were analyzed (Table 3). The pH of distilled water was 5.58, while the wastewater had a slightly alkaline pH of 7.14. This difference is attributed to various chemical compounds and microorganisms in wastewater, which tend to neutralize acidity (Gallo et al., 2016). The pH value of the wastewater falls within the acceptable range established by Resolution 0631 of 2015 (6–9), issued by the Colombian Ministry of Environment and Sustainable Development. Monitoring pH is essential to ensure that chemical or biological reactions occur efficiently during treatment (Mendoza et al., 2021).

Mera et al. (2016) highlights that wastewater pH can vary depending on the sample's age. Over time, processes such as organic matter degradation, methane fermentation, ammonium nitrification, and sulfide oxidation can occur, increasing carbon dioxide concentration and reducing pH. Therefore, maintaining stable pH levels is crucial for optimal treatment performance.

Temperature values were 23.3°C for distilled water and 27.2°C for wastewater, both within acceptable limits, as the maximum permitted temperature for surface discharge is 40°C (Resolution 0631, 2015).

Electrical conductivity was 2.10 µS cm^{-1} for distilled water and 731 µS cm^{-1} for wastewater, indicating the presence of dissolved salts and other elements (Quezada and Lacayo, 2020). According to Mera et al. (2016), values below 3000 µS cm^{-1} are desirable, as higher conductivity can hinder nutrient absorption by aquatic organisms due to increased energy demand.

Table 3. Evaluation of palm oil seed shell and fiber as a bioadsorbent.

Samples	pH	Temperature (°C)	Conductivity (µS cm-1)	Salinity (g l-1)	NO2 (mg l-1)	PO4 (mg l-1)	SO4 (mg l-1)
DW	5.58	23.30	2.10	0.00	0.00	0.00	0.00
DWS-1	6.30	25.50	31.00	0.00	0.00	0.00	0.00
DWS-2	6.69	24.10	45.00	0.00	0.00	0.00	0.00
DWS-3	7.50	23.60	22.10	0.00	0.00	0.00	0.00
DWF-1	6.30	25.50	31.00	0.00	0.00	0.00	0.00
DWF-2	6.70	24.10	28.00	0.00	0.00	0.00	0.00
DWF-3	7.50	23.60	27.00	0.00	0.00	0.00	0.00
WW	7.14	27.20	731.00	0.40	0.031	27.10	8.00
WWS-1	7.54	25.50	696.00	0.40	0.030	36.90	11.00
WWS-2	7.51	26.00	690.00	0.30	0.026	19.30	9.00
WWS-3	7.50	24.60	671.00	0.30	0.013	29.60	32.00
WWF-1	7.54	25.50	683.00	0.40	0.020	25.60	7.00
WWF-2	7.51	26.00	615.00	0.30	0.009	21.60	2.00
WWF-3	7.50	24.60	610.00	0.20	0.002	20.00	1.00

Table 3 confirms that the wastewater's salinity (0.4 g L^{-1}) was low, as expected for non-marine samples. Low salinity is important to avoid interference in adsorption processes (Vadell et al., 2015). As expected, NO2, PO4, and SO4 were not detected in distilled water, although trace contamination may occur due to residual impurities in lab equipment or incomplete distillation (Checmapocco and Hoyos, 2022). Although Colombian regulations (Resolution 0631 of 2015) do not set specific limits for phosphates and sulfates, their monitoring is essential due to their role in eutrophication (Mera et al., 2016). High nutrient levels in wastewater can stimulate algae growth, reduce dissolved oxygen, and disrupt aquatic ecosystems.

Using palm oil by-products as bioadsorbents (shell and fiber) represents a sustainable alternative to mitigate nutrient loads in wastewater, aligned with SDG 6 on clean water and sanitation. These materials demonstrated the capacity to neutralize acidic compounds and stabilize pH around 7.5, suggesting buffering behavior (Mondragón and Alfonso, 2020). Electrical conductivity increased in distilled water after adding shell and fiber, due to the leaching of minerals and ions like K^+, Na^+, Ca^{2+}, and Mg^{2+} (Romero, 2017). However, in wastewater samples treated with these materials, conductivity decreased by 4.8%, 5.6%, and 8.2% for shell concentrations of 6, 12, and 18 g L^{-1}, respectively. This suggests that the materials contributed to the removal of ionic substances, reducing overall conductivity (Moreno, 2013; Rodríguez and Sangucho, 2018). A similar trend was observed in salinity reduction at higher concentrations.

Nitrite concentrations in wastewater decreased with increasing adsorbent dosage. Using shell, removal percentages were 3.23%, 16.13%, and 58.06% for 6, 12, and 18 g L^{-1}, respectively. With fiber, these values were significantly higher: 35.48%, 70.97%, and 93.55%. This confirms effective nitrite adsorption by both materials, particularly fiber, likely due to its high surface area and porous structure (Mondragón and Alfonso, 2020; Rodríguez and Sangucho, 2018).

Phosphate removal using shell was observed only at 12 g L^{-1} (28.78%). This may be explained by the saturation of adsorption sites or phosphate release from the material (Rodríguez and Sangucho, 2018). Fiber, on the other hand, showed increasing removal with dosage: 5.54%, 20.30%, and 26.20% at 6, 12, and 18 g g L^{-1}, respectively. In treatments DWS-2 and DWS-3 (with distilled water), phosphate removal occurred despite only differing in shell concentration. This may reflect non-linear adsorption behavior, where higher dosage does not always increase removal due to saturation or ion competition. Phosphates naturally present in the bioadsorbent or released during treatment could also influence results, especially in systems with negligible background concentrations (Rodríguez and Sangucho, 2018).

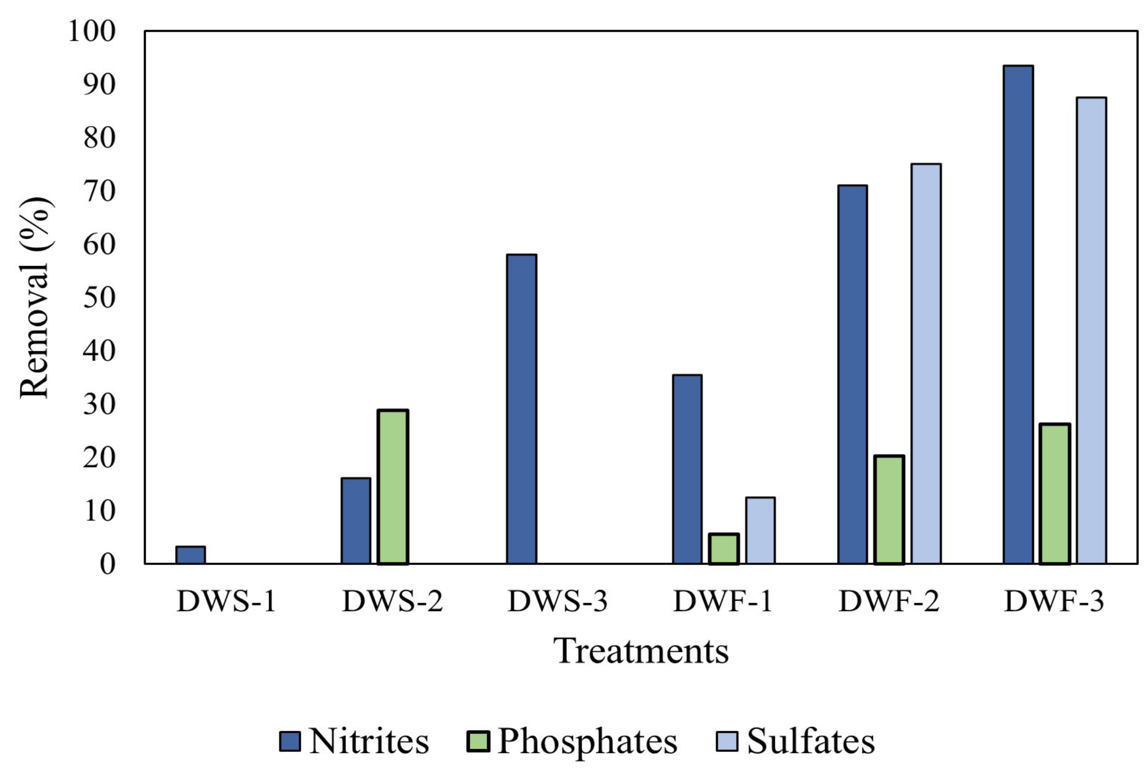
Sulfate removal showed a trend like phosphates. The shell demonstrated limited capacity, while fiber exhibited a dose-dependent improvement: 12.5%, 75.0%, and 87.5% at increasing concentrations. These results highlight fiber's potential as an efficient sulfate adsorbent.

Overall, Table 3 confirms that the fiber was more effective than the shell across all three nutrients. Maximum removal values for fiber were 93.55% (NO_2^-), 87.50% (SO_4^{2-}), and 26.20% (PO_4^{3-}), while shell reached 58.06% (NO_2^-) and 28.78% (PO_4^{3-}), with negligible sulfate removal. This demonstrates the greater efficiency of the fiber in domestic wastewater treatment. The adsorbent's effectiveness depends on surface area, pore structure, and surface functional groups. Materials with larger specific areas and appropriate pore sizes can absorb a wider range of contaminants

(Valladares et al., 2024). Functional groups such as carboxyl and hydroxyl groups facilitate interactions with pollutants (Amores, 2021; Oyehan et al., 2022).

Palm oil fiber is a lignocellulosic residue rich in lignin and cellulose, which enhances its adsorption capacity. It also contains minerals like calcium and silica, enabling both physical adsorption and ion exchange with organic and inorganic pollutants (Morante et al., 2022; Moreno, 2020; Martinez and Naranjo, 2021).

Figure 2. Removal percentage of shell and fiber at different concentrations.



The adsorbent's effectiveness depends on surface area, pore structure, and surface functional groups. Materials with larger specific areas and appropriate pore sizes can absorb a wider range of contaminants (Valladares et al., 2024). Functional groups such as carboxyl and hydroxyl groups facilitate interactions with pollutants (Amores, 2021; Oyehan et al., 2022). Palm oil fiber is a lignocellulosic residue rich in lignin and cellulose, which enhances its adsorption capacity. It also contains minerals like calcium and silica, enabling both physical adsorption and ion exchange with organic and inorganic pollutants (Morante et al., 2022; Moreno, 2020; Martinez and Naranjo, 2021).

Conversely, the shell showed lower performance, possibly due to ion competition in the wastewater. Competing substances may occupy active sites, limiting adsorption of the target pollutants (Pérez, 2019; Martínez et al., 2020; Liew et al., 2018). Although conventional adsorbents such as activated carbon, alumina, and synthetic resins are effective, their high cost makes alternatives like zeolites, clays, and agricultural waste attractive (Rivera and Acuña, 2021). This study supports the viability of using palm oil by-products as a low-cost, sustainable option for wastewater treatment.

To address challenges such as ion competition and variable adsorption efficiency, various strategies are recommended. These include chemical or thermal modification of the adsorbent, optimization of operational parameters (pH, temperature, contact time), and combining bioadsorbents with conventional materials to enhance performance (Amores, 2021; Moreno, 2020; Gallo et al., 2016; Barbosa et al., 2021; Georgin et al., 2023). Kinetic and isothermal studies are also essential to guide process optimization and scale-up (Cavazos, 2021; Valladares et al., 2024).

The properties of the adsorbent play a key role in the adsorption process. A larger specific surface area provides more active sites, enhancing the material's capacity to retain pollutants. Pore size and volume are also essential, as a suitable pore distribution facilitates the efficient capture of various contaminants. According to Valladares et al. (2024), an appropriate pore size distribution allows for more effective adsorption performance. Moreover, the chemical composition of the adsorbent—particularly the presence of functional groups such as carboxyl and hydroxyl—can significantly influence pollutant binding, improving interaction with specific compounds (Amores, 2021; Oyehan et al., 2022).

Palm oil rachis is a fibrous, lignocellulosic biomass with high organic content, including lignin and cellulose, as well as mineral components like silica and calcium, which enhance adsorption performance (Morante et al., 2022; Moreno, 2020; Alvarez, 2020; Garcia-Nunez et al., 2016). These characteristics provide a large surface area that facilitates both physical adsorption and chemical interactions. Organic compounds can be captured through surface adsorption forces, while functional groups in lignin and cellulose enable interactions with inorganic contaminants, such as metal ions, via ion exchange mechanisms or other surface reactions (Martinez and Naranjo, 2021; Oyehan et al., 2022). These properties make palm residues effective bioadsorbents for the removal of nitrates, phosphates, and sulfates from wastewater (Liew et al., 2018; Rodríguez and Sangucho, 2018).

In contrast, the lower adsorption capacity observed for the shell may be due to the presence of additional ions or interfering substances in the wastewater. These compete for adsorption sites on the material's surface (Pérez, 2019), reducing its effectiveness in targeting specific pollutants (Martínez et al., 2020; Liew et al., 2018). Therefore, it is essential to consider the complete composition of the treated water when evaluating adsorbent efficiency, particularly under real environmental conditions.

Conventional adsorbents widely used in wastewater treatment include silica gel, alumina, synthetic resins, and especially activated carbon. However, the high cost of these materials has driven the search for more affordable alternatives such as zeolites, clays, silicates, and organic waste (Rivera and Acuña, 2021). Continuous research has led to the exploration of diverse low-cost materials, such as those proposed in this study, which originate from agro-industrial residues and offer an economically and environmentally viable alternative.

Furthermore, several strategies can be implemented to overcome the observed limitations. For example, pre-treatment or chemical functionalization of bioadsorbents (using acids, bases, or metal salts) can increase the availability and affinity of active sites for target pollutants (Amores, 2021; Moreno, 2020). Adjusting operating conditions—such as pH, contact time, and temperature—can also improve selectivity and reduce ion competition (Gallo et al., 2016; Rodríguez and Sangucho, 2018). Integrating bioadsorbents with conventional materials like activated carbon or zeolites can further enhance adsorption efficiency (Barbosa et al., 2021; Georgin et al., 2023). Finally, conducting kinetic and isotherm modeling studies is essential for identifying optimal operating conditions and supporting the scale-up of these technologies (Valladares et al., 2024; Cavazos, 2021).

4. Conclusions

The application of palm oil-derived shell and fiber as bioadsorbents has demonstrated significant potential in enhancing wastewater quality, particularly in the removal of nutrients such as sulfates, nitrites, and phosphates. The fiber exhibited superior adsorption capacities, achieving removal efficiencies of up to 95.55% for nitrites, 87.50% for sulfates, and 26.20% for phosphates. In contrast, the shell achieved removal rates of 58.06% for nitrites and 28.78% for phosphates, with no notable sulfate removal. The enhanced performance of the fiber is attributed to its porous structure, which facilitates greater ion and nutrient adsorption. Despite these promising results, further research is warranted to optimize the fiber's application. Investigations into thermal modifications, operating conditions, and adsorption kinetics are essential to improve their efficiency in nutrient removal from wastewater. These findings contribute valuable insights into sustainable wastewater treatment practices and support progress toward the United Nations Sustainable Development Goals (SDGs), particularly SDG 6.3, which aims to improve water quality by reducing pollution and minimizing the release of hazardous chemicals. The implementation of such bioadsorbents not only enhances treated water quality but also promotes sustainable and responsible water resource management.

Conflict of Interest

The authors declare that they have no conflict of interest.

Declaration of competing interests

The authors affirm that there are no conflicts of interest to disclose.

Author contributions

Bleidy Ortega Vergara: conceptualization, methodology, data curation, writing—original draft, and project administration; Oscar Beleño Lozano: data collection, and analysis; Jennifer Villa Parra: data collection, and analysis; Hugo Hernández Palma: manuscript reviewing; Alcindo Neckel: conceptualization, reviewing final version; Andrea Liliana Moreno-Ríos: conceptualization, data curation, analysis, writing—original draft; Karen Esther Muñoz Salas: conceptualization, data curation, analysis, writing—original draft; Claudete Gindri Ramos: conceptualization, data curation, analysis, writing—original draft.

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