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Utilization of Jenitri as A Bioadsorbent in Petroleum Field-Produced Water

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ABSTRACT - As oil and gas fields mature, the volume of produced water can increase substantially, often exceeding 90% of total production. This water cannot be directly discharged or reused due to harmful contaminants that pose considerable environmental risks. One major challenge is the absence of efficient, eco-friendly, and cost-effective filtration media for its treatment. This study aimed to develop and assess an alternative adsorbent derived from jenitri seeds, chemically activated with potassium hydroxide (KOH) at controlled temperatures. The primary goal was to identify a more effective and sustainable adsorbent than those currently used in oilfield operations. The methodology involved the preparation of this adsorbent, Its physicochemical characterization included bulk density measurement, scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) analyses, along with performance testing through filtration, benchmarked against natural adsorbents such as candlenut and walnut. The KOH-activated jenitri demonstrated superior pollutant removal performance, primarily due to enhanced porosity and surface area resulting from the activation process. It exhibited the lowest bulk density (0.6 g/mL), an optimal porous structure as revealed by SEM, and the presence of active functional groups such as –OH, C=O, and C–O, identified through FTIR analysis. In filtration tests, KOH-activated jenitri effectively reduced total dissolved solids (TDS) to 600 mg/L and turbidity to 100–200 nephelometric turbidity units (NTU), outperforming natural jenitri, candlenut, and walnut, whose limited porosity contributed to lower adsorption efficiency

Keywords: adsorbent, potassium hydroxide, jenitri, filtration, produced water.

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INTRODUCTION

The management of produced water is a distinct and complex process, separate from oil and gas extraction, and represents a significant challenge for the industry (Klemz et al. 2021; Liu et al. 2021). Produced water refers to water that is brought to the surface along with oil and gas from the reservoir. It is the largest waste stream generated in oilfield operations and frequently exceeds environmental quality standards (Danforth et al. 2020)(Danforth et al. 2019)(McLaughlin et al. 2020). As oil and gas fields mature, the volume of produced water can rise dramatically, often surpassing 90% of total production, thus making its effective treatment increasingly critical (Shang et al., 2020)(Al-Rubaye et al., 2023)(Yuliusman et al. 2017).

Produced fluids refer to water generated during oil and gas production that cannot be directly discharged or reused (Fakhru'l-Razi et al. 2009)(Andhika et al. 2024). The presence of contaminants in produced water has become a growing global concern due to their potentially harmful environmental effects (Ganat et al., 2020)(Afdhol et al. 2024). In response, the Indonesian government has implemented strict regulations governing the treatment and disposal of produced water (Iihqgl et al. 2019; Afdhol et al. 2023). One of the primary challenges in treating produced water is the removal of residual oil that remains after the oil–water separation process, along with elevated concentrations of salts and acids. Chemical additives are often used to enhance the separation of oil from water by facilitating mechanical separation (Tjuwati Makmur 2013). Nevertheless, even after treatment, produced water typically contains oil concentrations ranging from 10 to 40 ppm at the point of discharge.

The materials used in this study include candlenut seeds and jenitri seeds, both chemically activated with potassium hydroxide (KOH). Filtration tests were carried out using formation water samples obtained from Field X. The research methodology included the preparation of adsorbents, their physicochemical characterization, and filtration tests conducted at a controlled temperature.

The primary objective of this study was to identify and compare existing oilfield adsorbents with those derived from jenitri seeds. This research aimed to explore the potential of jenitri seeds as a viable alternative to commonly used oilfield adsorbents, thereby reducing reliance on imported walnut-based materials. Additionally, the study seeks to ensure that treated produced water meets environmental quality standards before being reinjected into reservoirs or discharged into surface water bodies.

METHODOLOGY

The experiment was conducted by first activating the samples, followed by characterization tests on each sample, and finally, performing filtration tests.

Adsorbent production

The *jenitri* seeds were first crushed, as illustrated in Figure 1, and then sieved to achieve a uniform particle size using a mesh 16 screen. Once uniformity was ensured, the seeds were oven-dried for 1 h to eliminate any moisture. This study conducted testing on both oven-dried and chemically activated samples. Following the drying process, chemical activation was performed using a potassium hydroxide (KOH) solution for 1 h (Okman et al. 2014; Kane et al., 2016; Yuliusman, Afdhol, & Sanal 2018; Afdhol et al. 2024; Perdana et al. 2023; Kathi et al. 2024; and Yuliusman et al. 2018).

The activated *jenitri* seeds were thoroughly washed until a neutral pH was achieved, ensuring that residual chemicals from the activation process would not contaminate the produced water during filtration. Maintaining a neutral pH in the filtration medium is essential to prevent contamination. Once a neutral pH was confirmed, the samples were oven-dried prior to further testing.

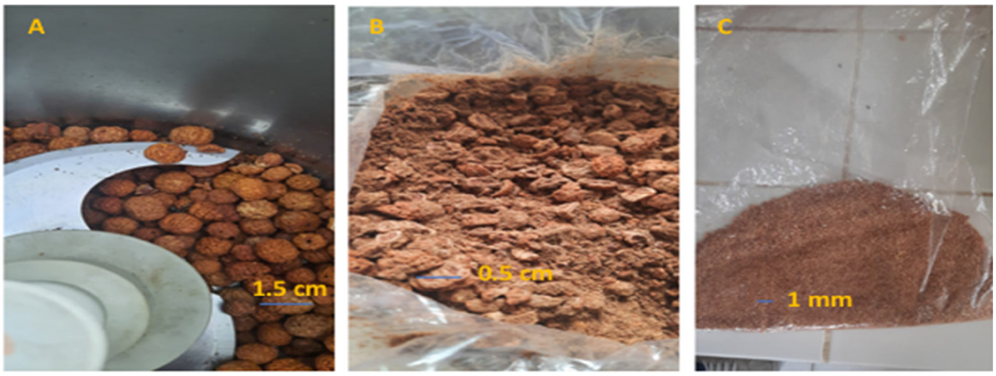

Figure 1
Crushing jenitri

Sample characterization

Bulk density

In this study, bulk density characterization tests were performed to evaluate the suitability of *jenitri* seed as a filtration medium, with a focus on its adsorption capacity (A.K. Nayak & Pal 2021) citric and tartaric acids. The carboxylic acid-modified OAES materials were used for the removal of hazardous gentian violet (GV. Bulk density measurements indicate the amount of material that can occupy a given volume, offering valuable insights into the material's porosity (Zhao et al. 2021). A higher bulk density suggests fewer pore spaces, which may negatively impact filtration efficiency (Sharma & Yortsos 1987).

The bulk density test was conducted using *jenitri* seeds as the test material. The procedure involved placing the seeds into a graduated cylinder and recording the initial volume. The cylinder was then subjected to tapping using a tapped density meter. Two tests were performed in this study one after 500 taps and another after 1,250 taps. Following each test, the final volume of the *jenitri* seeds was measured. To ensure consistency and accuracy, the difference in volume between the 500- and 1,250-tap measurements was required to remain within a threshold of two units.

The bulk density was calculated using the following equation:

$$\rho_{bulk} = \frac{m}{V_{bulk}} \tag{1}$$

FTIR

FTIR Fourier transform infrared spectroscopy (FTIR) is an analytical technique used to identify and analyze the chemical structure of various sample types, including solids, liquids, and gases (Ghazali & Azhar 2023)(Nandiyanto et al. 2019). The technique works by exposing the sample to infrared radiation, which induces molecular vibrations at specific frequencies (Berthomieu & Hienerwadel 2009; Nagabalasubramanian & Periandy. 2010). Different types of chemical bonds absorb radiation at characteristic wavelengths, producing a unique spectrum often referred to as the "molecular fingerprint" (Nandiyanto et al. 2022; Movasaghi et al. 2008).

SEM

Scanning electron microscopy (SEM) is a microscopy technique that uses electron scanning to capture high-resolution images of a sample's surface (Inkson 2016). In this process, a finely focused electron beam is directed at the sample's surface, generating secondary signals such as X-rays and secondary electrons (Koga et al. 2021; Cretu et al. 2015). These signals are then processed to create images that provide insights into the sample's topography and chemical composition. SEM-based morphological analysis can be performed at micrometer to nanometer scales, offering detailed information on surface structure, particle size, and shape distribution (Hochstrasser et al. 2021; Kim et al. 2020).

Filtration tests

Filtration tests are conducted to ensure that treated produced water meets environmental quality standards (Halim & Fatah 2023). The primary goal of the filtration process is to remove fine particles and residual oil from the produced water.

The process begins by measuring the turbidity level of the produced water sample. The water is then heated to 40°C and directed into a cooling tube before passing through a filtration funnel filled with *jenitri* seed media. As the water flows through the *jenitri*-based filter, it captures free particles and residual oil.

After passing through the filter, the water is collected for turbidity measurement to assess the water quality before and after filtration. A turbidimeter is used to measure nephelometric turbidity units (NTU), providing a quantitative evaluation of the filtration efficiency.

The total dissolved solids (TDS) are calculated using the following equation:

$$Total\ Dissolved\ Salts\ = k \times Electrical\ Conductivity$$

The turbidity measurement using a turbidimeter is calculated using the following equation:

$$Turbiditi = -log\ (\frac{I}{I_o}) \quad (2)$$

RESULT AND DISCUSSION

Bulk density characterization

As shown in Figure 2, the bulk density test results, obtained using the MM-0101 tapped density meter, revealed the bulk density of four types of bioadsorbents—candlenut (KMR), walnut (WN), jenitri (JNT), and jenitri treated with KOH (JNT + K). Candlenut exhibited the highest bulk density, approaching 0.75 g/mL, followed by walnut at approximately 0.7 g/mL, jenitri at approximately 0.65 g/mL, and then jenitri + KOH at 0.6 g/mL. The higher bulk density values of candlenut and walnut suggest a denser particle structure, meaning these materials contain more mass per unit volume. Adsorbents with higher bulk densities typically offer greater physical durability and the ability to absorb more material in a given space, making them suitable for applications requiring storage efficiency (Kunowsky et al., 2013). In contrast, jenitri and jenitri + KOH, which have lower bulk densities , display a more porous structure, especially after treatment with KOH. Chemical activation with KOH enhances the porosity and surface area of the adsorbent, which can considerably improve its capacity to adsorb pollutants such as heavy metals and organic compounds (Qu et al. 2020). The increased porosity provides more surface contact points for adsorbed substances (Prarat et al. 2019). Although a lower bulk density may reduce the material's physical compactness, the enhanced porosity can considerably improve its adsorption performance, positioning jenitri + KOH as a promising alternative for pollutant removal applications.

Functionally, adsorbents with high bulk density, such as candlenut, are better suited for applications that require storage of solid material within limited volumes (Kunowsky et al. 2013). In contrast, adsorbents with low bulk density and high porosity, such as jenitri + KOH, are more effective for filtration and pollutant absorption in liquids or gases, as they offer a larger surface area for adsorption (Zhao, Ma, et al. 2020). The balance between bulk density and porosity plays a crucial role in determining the efficiency and performance of an adsorbent in various environmental applications.

FTIR Results

As shown in Figure 3, the FTIR results, obtained using the IR Prestige-21 Shimadzu, revealed absorption peaks on bioadsorbents from candlenut, indicating the presence of specific functional groups on the adsorbent surface. The absorption peak at approximately 3,400–3,200 cm^{-1} corresponds to hydroxyl (–OH) groups, which are typical of alcohol or carboxyl groups in organic materials. The presence of these groups suggests that the adsorbent may interact with pollutant molecules through hydrogen bonding. Additionally, the strong peak near 2,900 cm^{-1} is attributed to the stretching vibration of aliphatic C–H bonds, commonly associated with the carbon chains in cellulose or lignin structures, which are found in candlenut, walnut, and *jenitri* adsorbents.

Additionally, the absorption peak at approximately 1,700–1,600 cm^{-1} indicates the presence of carbonyl (C=O) groups, which are commonly found in carboxylic acids or ketones. These functional groups are essential in the adsorption process, as they facilitate polar interactions with pollutant molecules.

Furthermore, peaks in the 1,200–1,000 cm^{-1} range correspond to C–O bond vibrations, typical of esters, ethers, and polysaccharide compounds. These functional groups enhance the reactivity of the adsorbent, allowing it to effectively interact with heavy metal ions or organic compounds, primarily through ion exchange or coordination covalent bonding. Functionally, the functional groups such as –OH, C=O, and C–O in the candlenut bioadsorbent are crucial for enhancing adsorption performance [29]. The hydroxyl (–OH) and carbonyl (C=O) groups create active sites on the material's surface, facilitating both chemical and physical interactions with pollutants, including heavy metals, organic compounds, and other polar substances (Yu et al. 2018). The presence of these functional groups enhances the adsorbent's capacity by facilitating hydrogen bonding, electrostatic interactions, and complexation. As a result, the functional group characteristics identified in the candlenut bioadsorbent through FTIR analysis highlight its potential as an effective material for adsorption applications in environmental processes, such as water purification and the removal of hazardous pollutants (Yang et al. 2019).

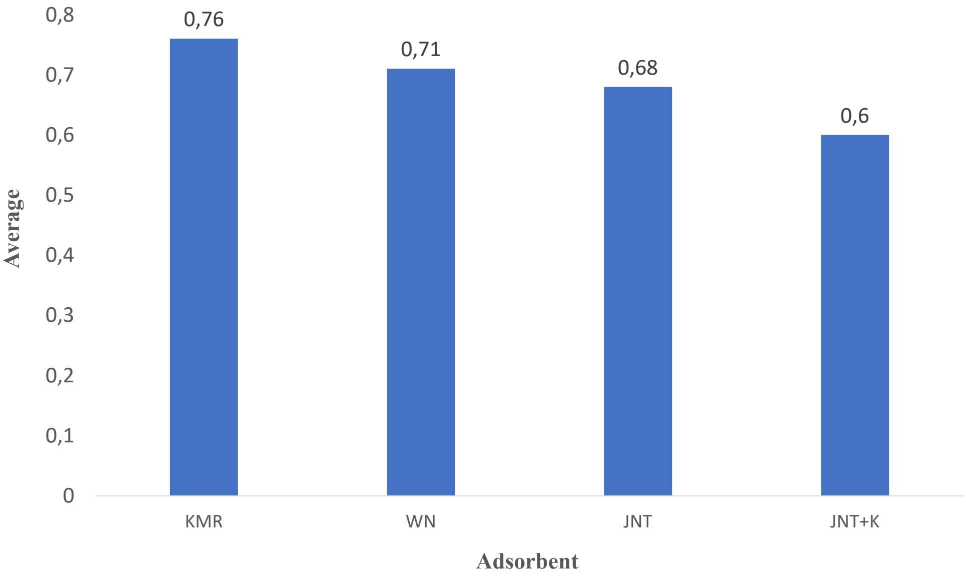

Figure 2
Bulk densities of some adsorbents

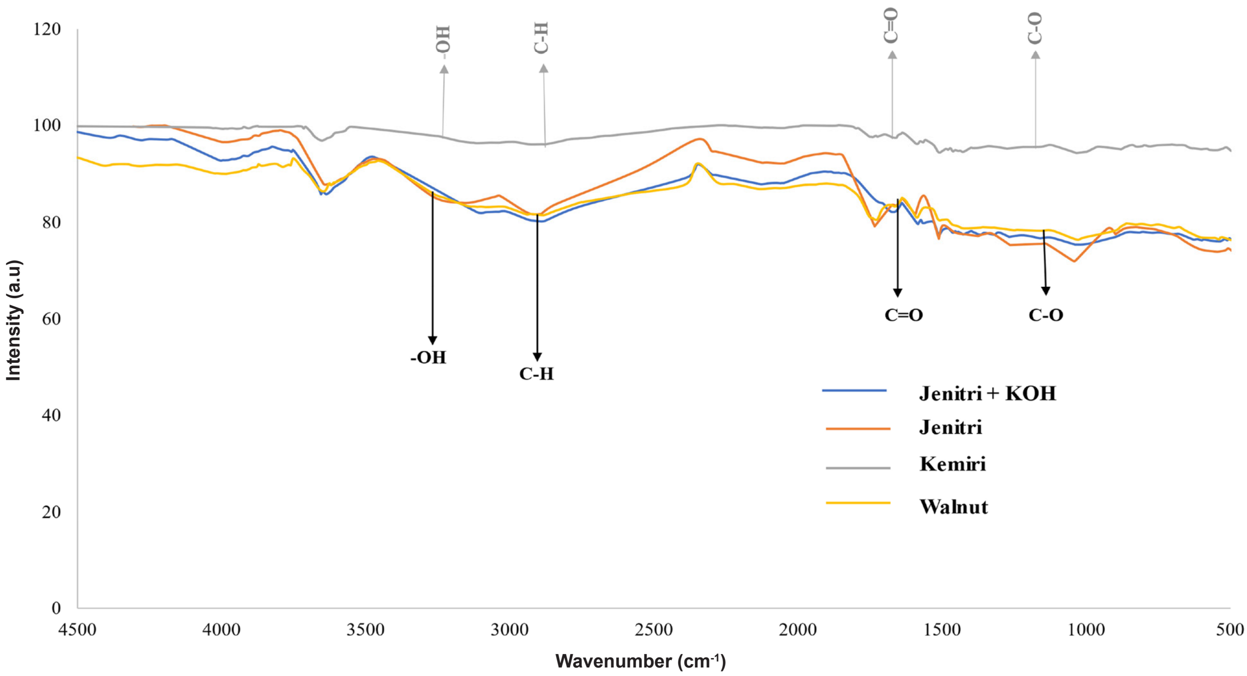

Figure 3
FTIR spectra

SEM characterization

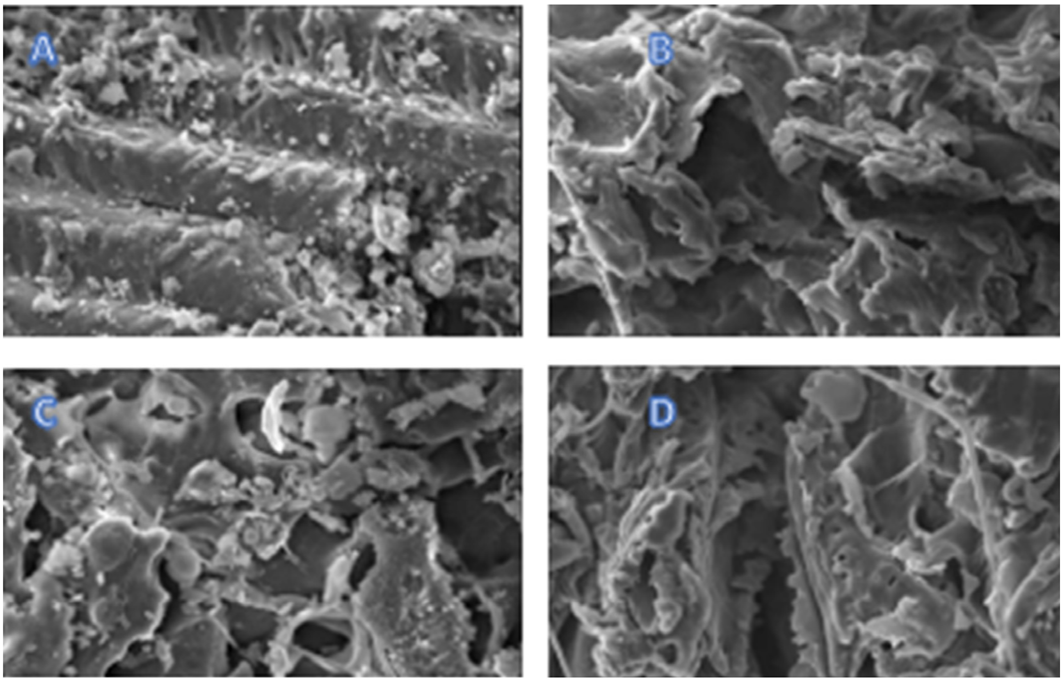

Figure 4
SEM characterization: (A) candlenut, (B) walnut, (C) jenitri, and (D) jenitri + KOH

As shown in Figure 4, the SEM results, obtained using the JSM-6460LA scanning electron microscope, reveal notable differences in the surface morphology of the bioadsorbents (A) candlenut, (B) walnut, (C) *jenitri*, and (D) *jenitri* + KOH which affect their adsorption performance. The candlenut (A) bioadsorbent displays a grooved surface with small pores and scattered particles on its surface, providing a large contact area for pollutant adsorption through physical mechanisms. In contrast, the walnut (B) bioadsorbent has a rough, irregular surface with smaller pores, which are still effective at adsorbing smaller pollutants, though its adsorption capacity is slightly lower than that of the other materials. The *jenitri* (C) bioadsorbent has a surface with small to medium-sized pores that are relatively evenly distributed, facilitating adsorption through the diffusion of pollutant molecules into the available cavities.

Chemical activation with KOH on *jenitri* (*jenitri* + KOH) caused considerable alterations to the surface structure, creating larger pores and a more open structure. This modification enhances the material's specific surface area and porosity, improving its ability to adsorb pollutants, particularly heavy metal ions and complex organic compounds (A. Nayak et al. 2017).

The open structure enhances interactions between pollutant molecules and active sites on the adsorbent surface. As a result, SEM confirmed that KOH treatment considerably improved the adsorption performance of *jenitri* compared to other bioadsorbents. The optimized porous structure of *jenitri* + KOH makes it the most promising material for waste treatment and environmental purification applications. Meanwhile, candlenut and walnut bioadsorbents continue to offer substantial potential for physical adsorption due to their grooved and rough surface structures.

Filtration tests

As shown in Figure 5, the filtration test results using the bioadsorbents candlenut, walnut, jenitri, and jenitri + KOH show variations in performance in reducing TDS levels at 40°C. The TDS values reflect the effectiveness of the bioadsorbents in removing pollutants. According to the graph, jenitri + KOH achieved the lowest TDS levels, ranging from 600 to 700 mg/L, and remained relatively stable after a certain point. This suggests that despite its high porosity and large surface area from KOH activation, some dissolved particles still passed through the filtration process. While chemical activation with

KOH enhances interactions with pollutants, the possibility of material degradation at 40°C may contribute to the observed increase in TDS levels. This indicates that while jenitri + KOH effectively adsorbs pollutants, further refinement in its stability and structural integrity may be required to minimize material leaching during filtration.

In contrast, the walnut bioadsorbent showed a notable increase in TDS, reaching approximately 600 mg/L, but stabilized more quickly than jenitri + KOH. The rough, less porous surface of walnut allows it to trap dissolved pollutants, although its efficiency is lower than materials with larger surface areas (Wiśniewska et al. 2024). Meanwhile, the candlenut bioadsorbent, despite its grooved structure observed in the SEM analysis, exhibited a lower TDS value, stabilizing at approximately 400 mg/L. This suggests that candlenut is effective at adsorbing a considerable portion of dissolved pollutants, though its performance is still lower than that of walnut and jenitri + KOH.

In contrast, jenitri without KOH demonstrated the best performance in maintaining TDS stability, with values of approximately 300–350 mg/L. This suggests that the natural jenitri bioadsorbent has an inherent ability to effectively absorb pollutants at 40°C, owing to its porous structure that facilitates the adsorption process. While KOH activation enhances porosity, it seems to contribute to the release of residues, resulting in higher TDS levels. This indicates that, although jenitri + KOH has an increased surface area for adsorption, untreated jenitri remains a more stable and efficient option for reducing dissolved solids in water treatment applications.

Overall, the jenitri bioadsorbent demonstrated the best performance in controlling TDS levels, while jenitri + KOH showed a high adsorption capacity but led to increased TDS due to the release of chemical activation residues. The candlenut and walnut bioadsorbents, while still promising, were less effective at reducing TDS compared to jenitri. These findings highlight that both the type of bioadsorbent and its treatment method considerably influence its filtration performance. The balance between porosity, surface area, and material stability is crucial in determining the effectiveness of adsorption for pollutant removal.

As shown in Figure 6, the turbidity test results using the bioadsorbents candlenut, walnut, jenitri, and jenitri + KOH revealed variations in their ability to filter suspended particles during the filtration process. Turbidity values reflect the concentration of suspended solids in the solution, offering insights into the effectiveness of each bioadsorbent. The walnut bioadsorbent exhibited the highest turbidity values, ranging from approximately 800 to 1,000 NTU, with substantial fluctuations. This suggests that, despite its rough surface structure, walnut's porosity is suboptimal, leading to insufficient retention of suspended particles during filtration. As a result, more particles remain in the solution, reducing filtration efficiency.

In contrast, the candlenut bioadsorbent showed more stable results than walnut, with turbidity values ranging from 600 to 700 NTU after an initial increase. The grooved structure observed in the SEM analysis enhances candlenut's ability to retain some suspended particles, but its efficiency in considerably reducing turbidity remains suboptimal. However, jenitri demonstrated superior performance, with lower and more stable turbidity values of approximately 200-300 NTU. The uniform pore structure of jenitri plays a key role in effectively trapping suspended particles, making it a highly efficient adsorbent for turbidity reduction.

The best results were achieved with jenitri + KOH, which exhibited the lowest and most stable turbidity values, ranging from 100 to 200 NTU. Chemical activation with KOH considerably enhanced the porosity and specific surface area of the jenitri bioadsorbent, allowing suspended particles to be efficiently captured within its pores and cavities. This optimized structure facilitates the effective filtration of solid particles, making jenitri + KOH the top-performing bioadsorbent for turbidity reduction in solution of those tested.

Overall, the performance variations among the four bioadsorbents highlight the crucial role of surface structure and porosity in filtration effectiveness. Jenitri + KOH outperformed the others in reducing turbidity, followed by jenitri, while candlenut and walnut demonstrated lower efficiency. Thus, KOH-activated jenitri has great potential for water treatment applications, particularly for considerably lowering turbidity levels (Zhao, Ma, et al. 2020).

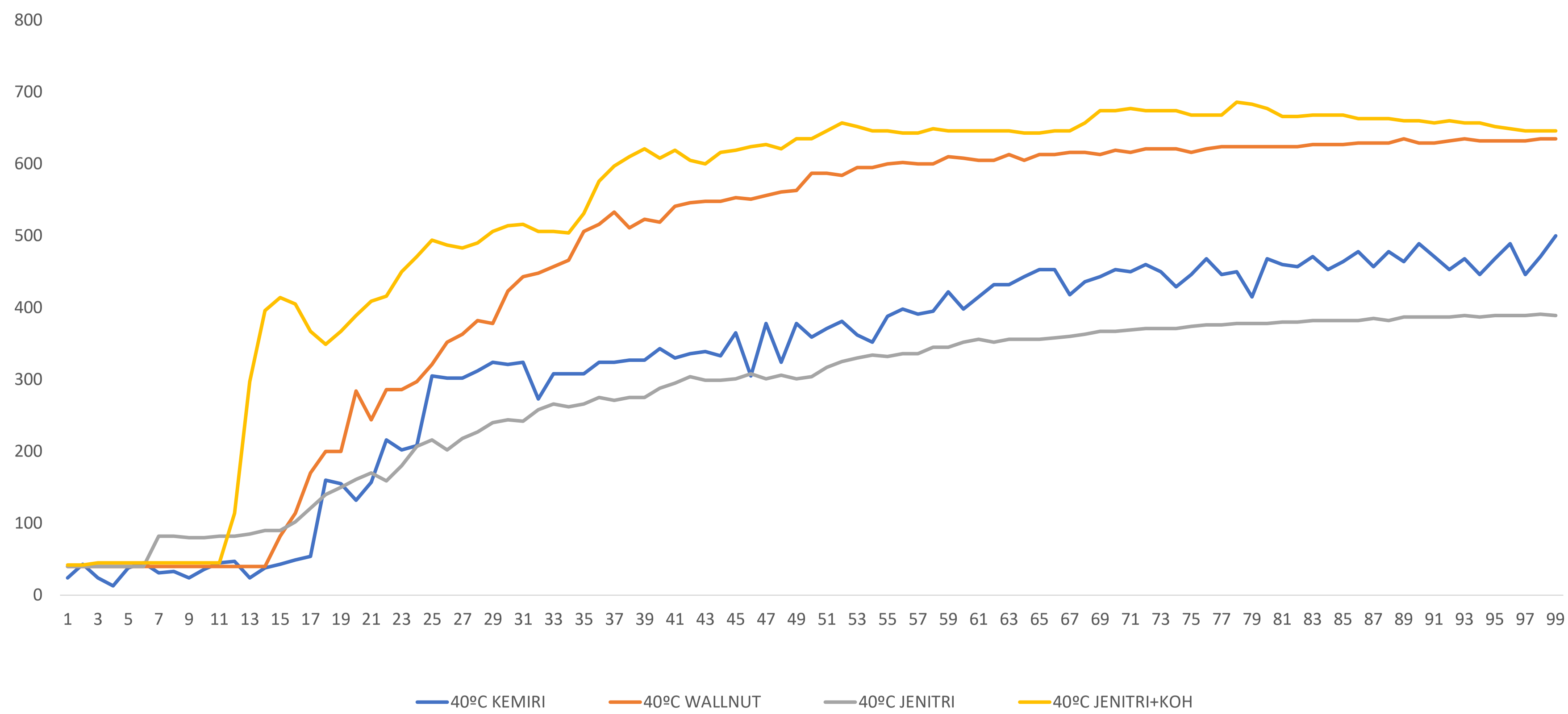

Figure 5
Total dissolved solids

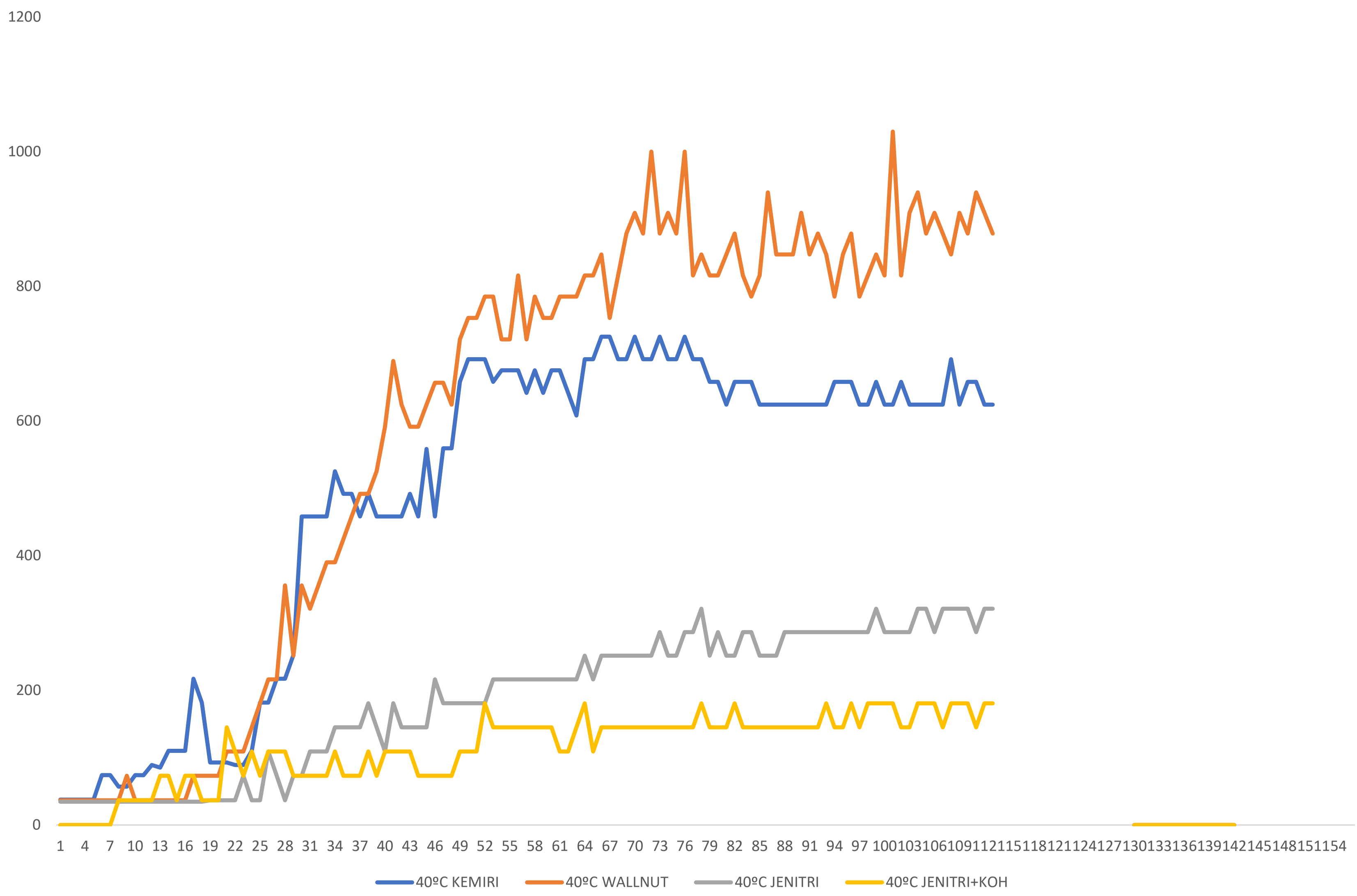

Figure 6 Turbidity

This research conducted on four types of bioadsorbents candlenut, walnut, *jenitri*, and jenitri + KOH shows a correlation between adsorption effectiveness and bioadsorbent properties.

In the bulk density characterization test, candlenut exhibited the highest bulk density, while *jenitri* + KOH showed the lowest. KOH activation has proven effective in enhancing both the physical and chemical properties of the adsorbent, thereby improving its interaction with the adsorbate compared to nonactivated materials. Several studies have demonstrated that KOH-activated adsorbents typically have a bulk density of 0.6 g/mL, as KOH treatment creates a more open pore structure, which is essential for the adsorption process. Consequently, KOH activation significantly boosts the adsorption performance of *jenitri* (Zhao, Ma, et al. 2020; da Paixão Cansado et al. 2019; Musah et al. 2024).

The FTIR results indicated that the characteristics of functional groups play a considerable role in determining adsorption efficiency. Modified bioadsorbents show strong potential for pollutant removal (Badawi et al. 2017). KOH activation of *jenitri* enhances its adsorption capacity, making it more effective in removing pollutants from water (El-Ghoul et al. 2021; Kasbaji et al. 2022). SEM analysis confirmed that KOH activation altered the bioadsorbent's internal structure, making it looser and more porous, while considerably increasing its specific surface area. This structural modification directly contributes to an enhanced adsorption capacity (Zhao, Junguan, et al. 2020).

The effectiveness of bioadsorbents such as candlenut, walnut, *jenitri*, and *jenitri* + KOH in reducing TDS levels at 40°C varies. Although *jenitri* + KOH shows promising physical characteristics, the results suggest that factors such as pore structure and chemical interactions may limit its effectiveness in lowering TDS levels. Previous studies have indicated that walnut as a bioadsorbent is more effective in reducing TDS (Hasanzadeh et al. 2020). However, based on our experimental data, *jenitri* exhibited the best performance in controlling TDS levels.

In terms of turbidity reduction, walnut showed the highest turbidity values with a rapid increase, followed by candlenut, which showed moderate turbidity levels. *Jenitri* showed reduced turbidity levels, and the addition of KOH further enhanced its ability to reduce turbidity. This improvement is attributed to chemical structural changes that influence emulsion stability, making KOH-activated *jenitri* the most effective bioadsorbent for turbidity reduction (Homayoonfal et al. 2015; Aeruginosa 2016).

Table 1
Turbidity reduction and TDS reduction comparison

Adsorbent	Turbidity Removal (%)	TDS Removal (%)	Notes	Ref
Tea Waste	54%	36%	Effective for multiple physiochemical attributes 1.	(Zaman et al., 2021)
Fe-Ni-Co Nanocomposite	98.5%	70%	High efficiency in batch adsorption 2.	(Iqbal et Al., 2022)
Maghemite Nanoparticles	89%	56%	Optimized conditions: pH 7, 0.75 g dose, 40 min contact 3 time.	(Iqbal et Al., 2021)
GAC + Zeolite + Pumice	90.27%	82.95%	Best performance in a horizontal series filter for greywater 4.	(Bahrami et al., 2021)

Table 1
Turbidity reduction and TDS reduction comparison (continued)

Adsorbent	Turbidity Removal (%)	TDS Removal (%)	Notes	Ref
PHKC (Kaolin + Hap + Starch)	97.07%	Not Specified	Effective for multiple wastewater treatment 5.	(Zaman et al., 2023)
Moringa Leaf Powder	75%	51%	High adsorption potential for various pollutants 6.	(Sharif et al., 2021)
Crab Shell Chitosan	Significant decrease	Significant decrease	Effective for tannery effluents, specific values not provided 7.	(Hossain et al., 2017)
Jenitri	High(93%)	High(95%)	High effective in adsorbing oil andreducing turbidity in produced water	
Jenitri Activited	High (96%)	High (97%)	Highly effective in adsorbing oil and reducing turbidity in produced water.	

CONCLUSION

The results indicate that the KOH-activated jenitri bioadsorbent outperforms the bioadsorbents currently used in oilfield applications. Consequently, walnut can be replaced by jenitri and jenitri + KOH, providing a more effective and locally available alternative for produced water treatment.

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GLOSSARY OF TERMS

Unit	Definition	Symbol
KOH	Potasssium Hydroxide	
TDS	Total Dissolved Solids	Mg/L
NTU	Nephelometric Turbidity Units	
FTIR	Fourier Transform Infrared Spectroscopy	
SEM	Scanning Electron Microscopy	
-OH	Hydroxyl group	
C=O	Carbonyl group	
C-O	Carboxyl group	
ρ_{bulk}	Bulk Density	gr/cc
KMR	Candlenut	
WN	Walnut	

JNT	Jenitri
JNT+K	Jenitri Activated with KOH

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