processes

*Article*

# Comparative Study of *Opuntia ficus-indica* Polymers, HPAM, and Their Mixture for Enhanced Oil Recovery in the Hassi Messaoud Reservoir, Algeria

**Kamila Bourkaib [1,*], Adel Elamri [2], Abdelkader Hadjsadok [1], Charaf Eddine Izountar [3], Mohamed Fouad Abimouloud [3], Amin Bouhafs [3], Ammar Isseri [3], Djamila Maatalah [4], Meriem Braik [5], Abdelali Guezei [6] and Omar Anis Harzallah [7,*]**

1 Laboratory of Functional Analysis of Chemical Processes, Faculty of Technology, Blida1 University, Blida 09000, Algeria; hadjsadok@yahoo.fr
2 MPTex Laboratory, National Engineering School of Monastir, University of Monastir, Monastir 5000, Tunisia; amri.adel2201@gmail.com
3 Imaging & CT Scanning Service, Direction of Laboratories and Central Core, Sonatrach, Hassi Messaoud 30500, Algeria; abimouloudf@gmail.com (M.F.A.); aminbouhafs@gmail.com (A.B.); isseriabya1@gmail.com (A.I.)
4 Production Division Hassi Messaoud, Sonatrach, Hassi Messaoud 30500, Algeria; djamilamaatallah@gmail.com
5 Research Unit Materials, Processes and Environment URMPE, Faculty of Technology, University M'hamed Bougara of Boumerdes, Boumerdes 35000, Algeria; meriem.braik@yahoo.com
6 Mewbourne School of Petroleum and Geological Engineering, Mewbourne College of Earth and Energy, The University of Oklahoma, Norman, OK 73019, USA; abdelaliguezei@yahoo.fr
7 LPMT UR 4365, Université de Haute-Alsace (UHA), 68093 Mulhouse, France
* Correspondence: bourkaibcamila@gmail.com (K.B.); omar.harzallah@uha.fr (O.A.H.)

**Abstract:** This study explores the potential of biopolymers as sustainable alternatives to synthetic polymers in enhanced oil recovery (EOR), aiming to reduce reliance on partially hydrolyzed polyacrylamides (HPAM). Mucilage extracted from *Opuntia ficus-indica* cladodes was investigated individually and in combination with HPAM in an 80/20 blend. The objective was to evaluate the physicochemical and rheological properties of these formulations, and their efficiency in improving oil recovery under realistic reservoir conditions. The materials were characterized using thermogravimetric analysis (TGA), X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier-transform infrared spectroscopy (FTIR). Rheological tests showed that both *Opuntia* mucilage and the HPAM–mucilage blend displayed favorable viscoelastic behavior in saline environments (2% NaCl) at high concentrations (10,000 ppm). The mucilage also exhibited thermal stability above 200 °C, making it suitable for harsh reservoir conditions. Core flooding experiments conducted at 120 °C using core plugs from Algerian reservoirs revealed enhanced oil recovery performance. The recovery factors were 63.3% for HPAM, 84.35% for *Opuntia* mucilage, and 94.28% for the HPAM–mucilage blend. These results highlight not only the synergistic effect of the blend but also the standalone efficiency of the natural biopolymer in improving oil mobility and pore permeability. This study confirms the viability of using locally sourced biopolymers in EOR strategies. *Opuntia ficus-indica* mucilage offers a cost-effective, eco-friendly, and thermally stable alternative to conventional polymers for enhanced oil recovery, particularly in saline and high-temperature reservoirs such as Hassi Messaoud in Algeria.

**Keywords:** enhanced oil recovery (EOR); mucilage; HPAM; *Opuntia ficus-indica*; Algerian reservoirs; ecological

check for updates

Academic Editor: Albert Ratner

Received: 3 April 2025
Revised: 26 May 2025
Accepted: 28 May 2025
Published: 5 June 2025

**Citation:** Bourkaib, K.; Elamri, A.; Hadjsadok, A.; Izountar, C.E.; Abimouloud, M.F.; Bouhafs, A.; Isseri, A.; Maatalah, D.; Braik, M.; Guezei, A.; et al. Comparative Study of *Opuntia ficus-indica* Polymers, HPAM, and Their Mixture for Enhanced Oil Recovery in the Hassi Messaoud Reservoir, Algeria. *Processes* **2025**, *13*, 1794. https://doi.org/10.3390/pr13061794

## 1. Introduction

Oil remains an essential energy resource for meeting global needs. Oil recovery occurs in three stages: primary, secondary, and tertiary (also called enhanced oil recovery (EOR)) [1]. Among EOR techniques, modified water injection—particularly water flooding—has gained increasing interest due to its relatively low cost [2–4]. Adding polymers to the injected water increases its viscosity, thereby improving the sweep efficiency of reservoirs and enhancing oil recovery [5–7].

Polymer mobility primarily influences the transport of polymers in porous systems [8,9], defined as the ratio between the polymer's viscosity and pore permeability [10–12]. This mobility depends on the balance between viscous forces, which facilitate polymer displacement, and capillary forces [13–15], which can slow or block their passage through the pores. A low-mobility polymer moves slowly but can penetrate smaller pores more effectively, optimizing oil recovery. Conversely, excessive mobility may lead to preferential flow, leaving certain reservoir zones unswept by the injected fluid.

Various parameters influence the performance of polymers in porous systems. Pore size and geometry determine whether polymers can flow freely or accumulate in restricted areas. Temperature plays a key role: at high temperatures, some polymers degrade, reducing their efficiency [16,17]. Additionally, flow velocity impacts the formation of viscoelastic structures, which are essential for maximizing oil recovery rates.

However, polymer efficiency is often diminished by retention mechanisms [18–20], such as mechanical trapping [21], adsorption [22], and hydrodynamic retention [23]. Mechanical trapping occurs when polymers are blocked in narrow pores, while adsorption on rock surfaces decreases their active concentration for displacing oil. Hydrodynamic retention refers to the fraction of polymers trapped in the porous medium due to fluid interactions, reducing their effectiveness [24].

Previous research on the use of HPAM in core flooding tests has demonstrated their potential in EOR applications while highlighting significant limitations, notably reduced effectiveness under high-salinity conditions [25–28]. Studies have shown that HPAM's viscosity and performance deteriorate in high salt concentrations, leading to less efficient oil recovery. In addition, large quantities of synthetic polymers are used in these EOR processes, which have negative ecological impacts on landfills.

To overcome these challenges, other biopolymers, such as Xanthan [29,30] and Guar Gum [31,32], have been explored in various contexts for EOR applications. However, these polymers face similar degradation issues under saline conditions and concerns regarding high costs. Research conducted in countries such as Saudi Arabia [33], Brazil [34], Pakistan [35], Egypt [36], Sudan [37], and Colombia [38] has consistently pointed out these constraints, indicating that while these biopolymers offer environmental advantages, their effectiveness in harsh reservoir domains remains limited.

Despite using various EOR techniques, much oil remains trapped in geological formations. Partially, hydrolyzed polyacrylamide is commonly used to improve the viscosity of injected water and thus to increase sweep efficiency. However, its performance is limited in environments with high salinity and temperature [39]. Studies conducted by Zhang [40] and Bo Wang [41] have highlighted a phenomenon of plugging caused by HPAM, where reservoir pores become clogged, reducing permeability and limiting recovery efficiency. These findings underscore the limitations of current methods, which struggle to enhance oil production under varying reservoir conditions [42,43].

Faced with these challenges, natural biopolymers, such as *Opuntia ficus-indica* mucilage, present promising alternatives. Their natural origin and biodegradability make them ideal candidates for industrial applications, particularly in EOR [44,45]. While this study is among the first to explore and apply this biopolymer in the context of EOR in Algerian reservoirs, further research is required to assess its scalability and long-term effectiveness. These initial findings open new avenues for integrating local and renewable resources into the oil industry. However, additional studies are essential to fully understand such materials' practical implications and potential in real-field conditions.

The cladode of *Opuntia ficus-indica* is used in various fields, including food [46] and cosmetics [47], due to its richness in mucilage and polysaccharides [48]. Regarding its rheological behavior, the mucilage from Opuntia exhibits interesting properties that make it comparable with other natural polymers such as Guar Gum [49] and Xanthan [50]. While these polymers are also used to enhance the viscosity of solutions, Opuntia's mucilage stands out for its better performance in saline environments and ability to maintain optimal viscoelastic properties, making it a promising alternative in environmentally friendly industrial applications.

In our comparative study of the performance of HPAM, Opuntia mucilage, and their blend, it is demonstrated that biopolymers can improve recovery efficiency under high-salinity conditions while reducing costs and environmental impacts. Furthermore, our approach aligns with an eco-responsible vision by promoting the use of local renewable resources to meet industrial needs [51].

This article evaluates the relevance of *Opuntia ficus-indica* mucilage as an alternative to HPAM in enhanced oil recovery techniques. Through a comparative study of these polymers' physicochemical and rheological properties and structural analyses of core plugs, it is determined whether their synergy can offer optimal performance in challenging reservoir conditions. This approach seeks to improve the efficiency of current methods and promotes the use of natural and local resources in a sector seeking sustainable innovation.

## 2. Geological Setting

The Hassi Messaoud oil field, located in the central Triassic basin of Algeria, is the country's largest oil field in terms of surface area and reserves. The field is bounded by several neighboring oil fields and geological structures: to the northwest lie the Ouargla fields; to the southwest, the El Gassi and Zotti fields; and to the southeast, the Rhourde El Baguel and Mesdar fields. The reservoir is situated within a dome structure formed by complex paleotectonic processes and represents an extension of a large regional ridge. This geological framework is typical of the northeastern Triassic province and provides the geological context for the core samples used in this study.

## 3. Materials and Methods

### *3.1. Isolation of Opuntia ficus-indica Powder and Fluid Preparation*

#### 3.1.1. Extraction of *Opuntia ficus-indica* Powder

For the experimental tests, the synthetic HPAM polymer (Flopaam 3130S, Mw: $3.5 \times 10^6$ g/mol, 30% hydrolysis degree) generously provided by SNF Floerger Andrézieux-Bouthéon, France was selected as the benchmark polymer.

The fine powder derived from the cladodes of *Opuntia ficus-indica* was harvested in the Tizi Ouzou (Algiers, Algeria) in January 2024. The extraction process involved meticulous steps: (i1) Before extraction, the cladodes were rinsed with water to remove any dust particles. (i2) The spines were carefully cut off with a knife, and the cladodes were peeled and chopped into pieces measuring 1–2 cm. (i3) These pieces were then frozen for 24 h. (i4) After freezing, three volumes of the cladodes were combined with one volume of distilled water at 40 °C using a thermostatic water bath (Julabo TW20, Seelbach, Germany). (i5) The resulting mixture was homogenized at room temperature using a high-speed laboratory blender (IKA T25 digital Ultra-Turrax, Staufen, Germany) for 5 min. (i6) It was then passed through a fine-mesh sieve to eliminate more extensive insoluble materials, followed by filtration through a sterile cloth to recover the mucilage. (i7) To precipitate the mucilage from the filtrate, three volumes of 96% ethanol were added while stirring at 350 rpm for one hour using a magnetic stirrer (VELP Scientifica AREX-6, Usmate Velate, Italy). (i8) The mucilage was collected via filtration, dried in an oven at 60 °C for 24 h (Memmert UF55 drying oven, Schwabach, Germany), and finally ground into a fine powder using a mortar [51].

3.1.2. Crude Oil and Brine

In this study, the salinity of an Algerian petroleum reservoir is simulated by preparing a saline solution containing 20 g/L of sodium chloride (NaCl) dissolved in deionized water (DW). The solution was prepared using a magnetic stirrer (VELP Scientifica AREX-6, Monza, Italy) and maintained at room temperature (20 ± 2 °C) to ensure complete dissolution. NaCl is selected for the simulated formation water to maintain a straightforward and controlled experimental approach. Using a common salt such as NaCl, The aim is to create a precise baseline for our research, enabling us to isolate the effects of particles and polymers. While the limitations of this simplified method are recognized, it serves as a crucial preliminary step in examining the fundamental interactions before tackling the more complex ionic compositions typically found in actual reservoir conditions. The crude oil utilized in this study was obtained from an Algerian oil field, exhibiting a density of 0.8401 g/cm$^3$, a viscosity of 6.0453 cP, and an API gravity of 36.93. These properties were measured at atmospheric pressure and a temperature of 25 °C using a digital density meter (Anton Paar DMA 5000, Graz, Austria), a Brookfield viscometer (DV3T model, Middleboro, MA, USA), and an API hydrometer, respectively.

3.1.3. Fluid Preparation

This study investigated a concentration of 10,000 ppm using a synthetic brine with a composition of 2% NaCl for both HPAM and *Opuntia ficus-indica* polymers. The HPAM solutions were meticulously prepared by dissolving the appropriate quantity of powder in water using a magnetic stirrer (VELP Scientifica AREX-6, Usmate Velate, Italy) at low-speed stirring (90 rpm) for 6 to 7 h at room temperature (20 ± 2 °C), resulting in homogeneous and transparent dispersions devoid of insoluble particles. This is essential to prevent pore blockage, as any undissolved particles may obstruct the porous network during injection.

*Opuntia ficus-indica* solutions were carefully prepared by mixing the suitable powders in synthetic brine and agitating for 10 h at room temperature (20 ± 2 °C) using the same magnetic stirrer. The HPAM and *Opuntia ficus-indica* solutions were securely stored in sealed containers and left undisturbed for 12 h to ensure complete hydration and prevent oxidation.

A synergistic blend of HPAM and *Opuntia ficus-indica* was also prepared with proportions of 80% HPAM and 20% *Opuntia ficus-indica* mucilage while maintaining a total concentration of 10,000 ppm [51]. This blend was formulated by dissolving both components in the synthetic brine. After uniform agitation for 10 h at room temperature (20 ± 2 °C), the solution was left to rest for 12 h in sealed containers to allow for optimal interaction between the two polymers, thus ensuring maximum homogeneity and stability.

3.1.4. Core Samples

Three identical plugs of Triassic clay-type rock were extracted from petroleum cores in the Hassi Messaoud reservoir, Algeria. Each plug had the following dimensions: a diameter of 2.45 cm, a length of 4.24 cm, and a mass of 47.16 g. The plugs exhibited a known porosity of 16.52% and a permeability of 206 md, making them suitable for simulating the petrophysical conditions encountered in this reservoir. This selection ensures that the experimental results accurately represent the fluid behavior in the targeted reservoir.

### 3.2. Physicochemical Analysis

#### 3.2.1. Thermal Analysis

Thermogravimetric analyses (TGAs) were conducted for *Opuntia ficus-indica* and HPAM powders using a TA instrument (SDT Q600 V20.9 Build 20, New Castle, DE, USA). Argon was used as the purge gas at a 100 mL/min flow rate. A dried powder sample of *Opuntia ficus-indica* and HPAM was placed in an aluminum vessel and heated from 25 to 1000 °C at 10 °C/min.

#### 3.2.2. Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray (EDX) Analysis

The morphology of the *Opuntia ficus-indica* powder, HPAM, and plug samples sourced from petroleum cores (before and after injection into the core flooding apparatus) were examined using scanning electron microscopy (SEM) with a CARL ZEISS EVO LS 10 from Germany. An energy-dispersive X-ray (EDX) detector was used for additional analyses to determine the elemental composition of both the powders and the core plugs, providing insights into the material interactions before and after polymer solution injection.

#### 3.2.3. X-Ray Diffraction (XRD) Analysis

For the XRD analysis, HPAM and *Opuntia ficus-indica powders* were loaded into aluminum sample holders and analyzed using a Rigaku Ultima IV diffractometer operating at 40 kV and 30 mA. The diffractometer used Cu-Kα radiation with a wavelength (λ) of 1.5406 Å. The analysis was also conducted on the core plugs before and after injection of the polymer solutions to assess any changes in crystallographic structure.

#### 3.2.4. Fourier-Transform Infrared (FTIR) Spectroscopy

Fourier-transform infrared spectrometry (Bruker Lances, TENSOR 27, Ettlingen, Germany) was employed to measure the FTIR spectra of the HPAM, *Opuntia ficus-indica* powder, and mixture. The frequency range used was from 400 to 4000 $cm^{-1}$.

#### 3.2.5. Rheological Measurements

The rheological properties were evaluated using a temperature-controlled rheometer with Peltier temperature control (Physica MCR302, Anton Paar, Graz, Austria). The measurement system had a cone-plate geometry (Φ60 mm, ⊖ = 1°, CP60/1). The tests were conducted on HPAM and *Opuntia ficus-indica* powder mixed at 80 °C using a synthetic brine solution with 2% NaCl.

#### 3.2.6. Assessment of Polymer Efficiency in Core Flooding Analysis

The experimental procedure for core flooding followed rigorous steps to ensure precise and reproducible results. Triassic clay–sandstone core plugs were prepared and inserted into the core flooding apparatus. Saturation of the medium was achieved by injecting a 20 g/L NaCl solution throughout 3 to 6 h. Subsequently, the injection system was set up with two BT series syringe pumps, allowing fluid injection at up to 5000 psi pressures. The thermostat-controlled oven maintained a temperature of 120 °C, chosen to simulate the reservoir's actual conditions. The core was saturated with the test fluid using a back-pressure regulator (BPR), increasing the interstitial pressure to fill all fluid pores.

Each experiment was conducted three times, once with HPAM, once with an *Opuntia ficus-indica* biopolymer, and once with their mixture, directly comparing their efficacy in enhanced oil recovery processes. Crude oil was injected at various rates (0.5, 1, and 1.5 mL/min) during the experiments. In contrast, polymer solutions at a concentration of 10,000 ppm (for both the HPAM and mucilage, as well as the mixed solution) were injected at corresponding rates. The pressure sensor system continuously monitored the pressure difference during flow, providing essential data for evaluating polymer displacement efficiency under reservoir conditions. Although these flow rates are higher than typical reservoir fluid velocities (~1 ft/day), such rates are commonly used in laboratory core flooding tests to shorten experimental time while still providing relevant and reliable insights into polymer behavior and displacement mechanisms. Figure 1 shows a schematic diagram of the displacement device.

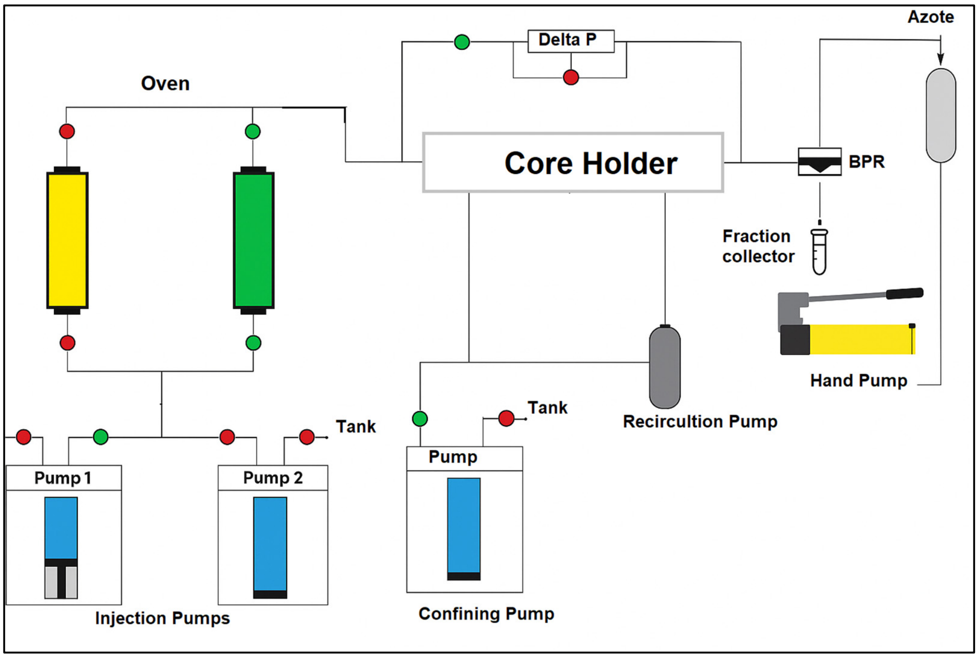


**Figure 1.** Core flooding CF350.

3.2.7. Statistical Analysis

All measurements were performed in triplicate, and the results are presented as mean ± standard deviation (SD).

## 4. Results and Discussion

### *4.1. Thermal Analysis*

Figure 2 illustrates the thermal behavior of the mucilage extracted from *Opuntia ficus-indica* cladodes and HPAM. A thermogravimetric analysis (TGA) reveals distinct zones of weight loss at different temperatures, providing insights into the thermal decomposition of the components present in these polymers.

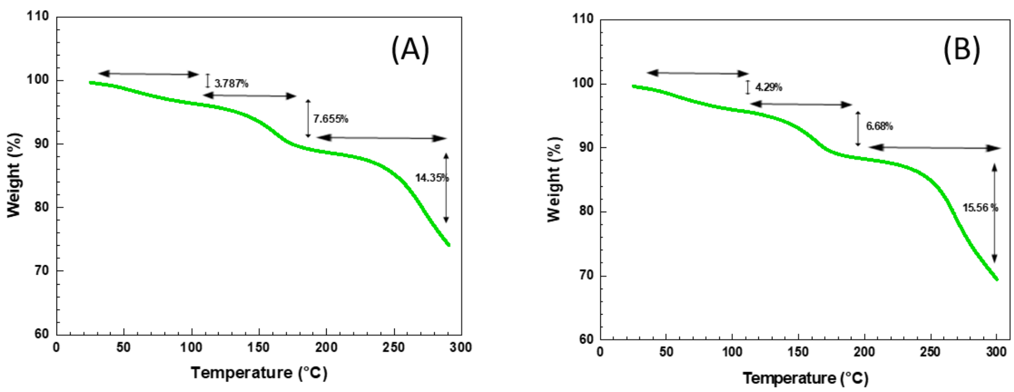


**Figure 2.** TGA of (**A**) mucilage and (**B**) HPAM.

As shown in Figure 2A, three major thermal events are identified during the characterization of mucilage. First, a weight loss of 3.787% is observed at 100 °C, attributed to the endothermic evaporation of absorbed water or moisture in the polymer [52,53]. While this loss is measurable, it is considered negligible, especially given the good temperatures in Algeria, which typically reach around 100 °C. This underscores the potential of mucilage in enhanced oil recovery (EOR) applications.

The second phenomenon, characterized by a weight loss of 7.695% at 200 °C, corresponds to the decomposition of organic components. This thermal behavior aligns with that observed in previous studies by Otálora et al. [54] and Manhivi et al. [55], who reported similar behaviors in various biopolymers.

Finally, the last thermal event occurs at 300 °C, resulting in a weight loss of 14.35%, indicating significant thermal degradation. This degradation may be related to the breakdown of components, such as chain breaks in polysaccharides and the decomposition of pectins [56].

In comparison, in Figure 2B, the HPAM, commonly used in EOR applications, exhibits similar thermal events. At 100 °C, a weight loss of 4.29% is observed, followed by a loss of 6.68% at 200 °C due to the decomposition of organic components and a notable thermal degradation of 15.56% at 300 °C [57,58]. Although the two polymers differ in chemical structures, their thermal behaviors are remarkably equivalent within the examined temperature range.

These findings suggest important implications for their combined use in enhanced oil recovery applications. The mucilage from *Opuntia ficus-indica* behaves similarly to HPAM, indicating that this biopolymer could be a promising alternative in EOR processes.

### *4.2. SEM and EDX Analysis*

Combined scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) analyses were conducted to study the morphology, geometric structure, distribution, and purity of the mucilage powder samples derived from the cladode of *Opuntia ficus-indica* and partially hydrolyzed polyacrylamide.

The results presented in Figure 3A indicate that mucilage particles exhibit a crystalline and irregular morphology, suggesting that the particles do not have an elongated shape. The surfaces of the particles display a marbled appearance, enhanced by wavy fibers, while their particle size distribution reveals heterogeneity. In contrast, HPAM, as shown in Figure 3B, presents a uniform and smooth morphology characteristic of synthetic polymers. This morphological uniformity promotes a more even distribution of particles in solution, leading to more predictable interactions with other enhanced oil recovery (EOR) system components. Previous studies have reported similar findings regarding the morphology of synthetic polymers, highlighting the significance of this characteristic for industrial applications [59].

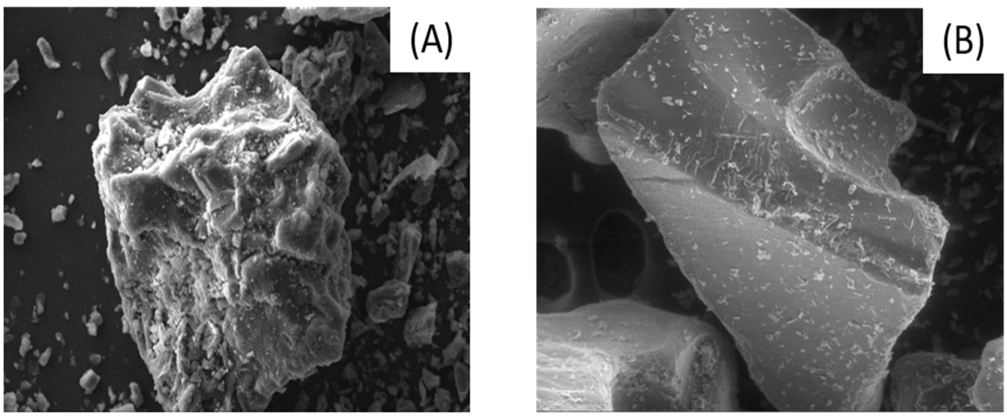


**Figure 3.** SEM micrographs of (**A**) mucilage and (**B**) HPAM at 10 μm scale.

Figure 4 illustrates the EDX analysis of the chemical elements present on the surface of the particles. The results for the cladode of *Opuntia ficus-indica*, presented in Figure 4A, reveal the presence of silicon, carbon, potassium, chlorine, magnesium, calcium, and oxygen. These identified mineral elements are consistent with those reported in the literature, underscoring the importance of the chemical composition of plant extracts in industrial applications [60]. In contrast, for HPAM, Figure 4B indicates the presence of carbon, oxygen, nitrogen, and sodium, characteristic elements of this synthetic polymer. The predominance of these elements reflects the chemical structure of HPAM [61], which may influence their viscoelastic properties and performance in enhanced oil recovery applications, as demonstrated by other studies.

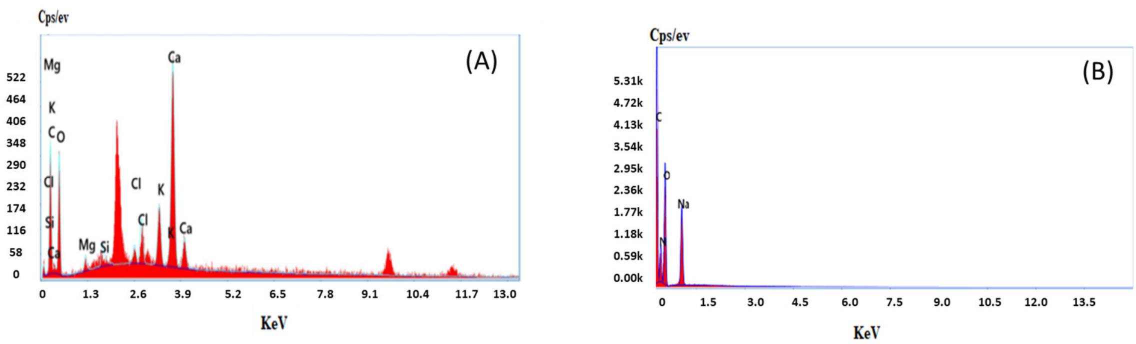


**Figure 4.** EDX analysis of (**A**) mucilage and (**B**) HPAM.

The SEM/EDX analysis reveals significant morphological and chemical distinctions between the mucilage from *Opuntia ficus-indica* and HPAM. These differences may lead to interesting synergistic interactions in enhanced oil recovery applications. With its complex structure, mucilage offers promising potential for improving interactions with porous surfaces, while HPAM provides the necessary stability to its viscoelastic properties. This synergy between the two polymers could optimize the efficiency of enhanced oil recovery processes, as suggested by several previous studies.

### *4.3. X-Ray Diffraction Analysis (XRD)*

The X-ray diffraction (XRD) experiments explored the structural differences between the mucilage extracted from *Opuntia ficus-indica* cladodes and partially amorphous polyacrylamide. The analysis results, illustrated in Figure 5, indicate that mucilage exhibits a crystalline structure with diffraction peaks at 15°, 25°, 32°, 38°, and 43°, corresponding to minerals such as calcium carbonate ($CaCO_3$), calcium magnesium bicarbonate ($CaMg(CO_3)_2$), magnesium oxide (MgO), potassium chloride (KCl), and silicon dioxide ($SiO_2$) in quartz form. These findings corroborate the findings from previous studies that highlighted the presence of these minerals in *Opuntia ficus-indica* extracts, emphasizing the influence of various environmental factors on their composition [62,63].

In contrast, the analysis of HPAM (presented in Figure 5) reveals no distinct diffraction peaks characteristic of amorphous materials. This absence of regular diffraction indicates a disordered arrangement of polymer chains, as demonstrated in numerous studies [64,65]. The structural differences observed between the crystalline mucilage and amorphous HPAM may significantly affect their performances in enhanced oil recovery applications. While mucilage, with its mineral composition, may provide stability or reactivity properties, HPAM may exhibit different interactions and behavior depending on the operational conditions.

These results underscore the importance of analyzing the mineral and structural composition of materials used in enhanced oil recovery processes, as these characteristics can directly influence the effectiveness of recovery methods.

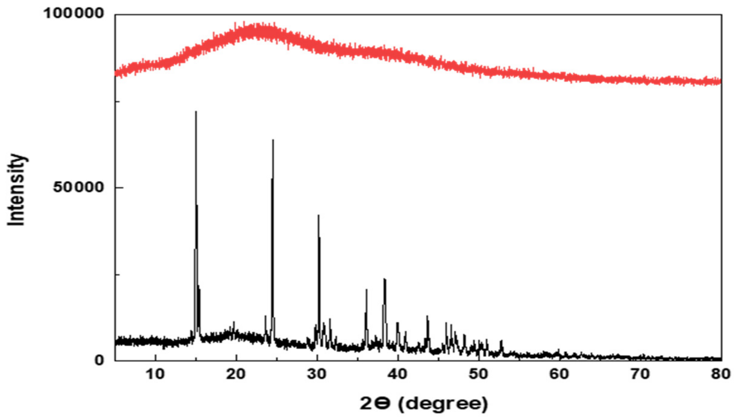


**Figure 5.** XRD spectra of mucilage (black) and HPAM (red).

### 4.4. FTIR Analysis

Fourier-transform infrared spectroscopy (FTIR) was employed to investigate and compare the molecular characteristics of hydrophilic polyacrylamide, the extract of the *Opuntia ficus-indica* powder, and the mixture. FTIR spectra were obtained for each sample to identify the present functional groups and to analyze their chemical structures.

In Figure 6, the FTIR analysis of the HPAM displays distinctive features. Notably, prominent peaks are observed at specific wavenumbers: 3182 $cm^{-1}$ signifies elongation vibrations attributed to N-H bonds, while 2937 $cm^{-1}$ and 1651 $cm^{-1}$ represent C-H deformation and vibration, respectively, associated with C=O functional groups. Discernible peaks ranging from 1317 to 1110 $cm^{-1}$ indicate C-O stretching vibrations [64,65].

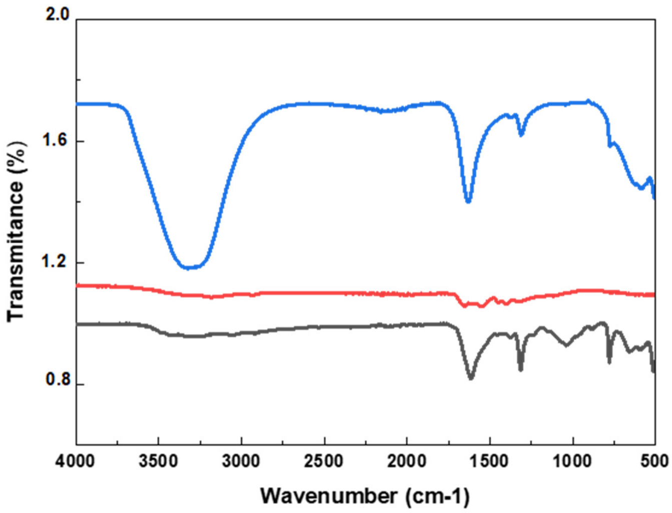


**Figure 6.** FTIR spectra of mucilage (black), HPAM (red), and mixed (blue) solutions.

In the spectrum of the *Opuntia ficus-indica* powder, the absorption band at 3255 $cm^{-1}$ indicates the presence of hydroxyl functional groups (-OH). The firm peaks observed at approximately 1615 $cm^{-1}$ and around 1314 $cm^{-1}$ are associated with the carbonyl (C=O) and ether (C-O) functional groups' elongation and deformation vibrations. The bands identified between 1040 and 778 $cm^{-1}$ are attributed to the stretching vibrations of the Si-O-Si group [66].

For the HPAM/mucilage mixture, a broad and intense band is observed between 3000 and 3500 $cm^{-1}$, corresponding to the elongation vibrations associated with N-H and O-H bonds. This indicates the formation of hydrogen bonds between the HPAM and mucilage groups. The peaks at 1631 $cm^{-1}$, 1379 $cm^{-1}$, and 773 $cm^{-1}$ are associated with the stretching and bending vibrations of -OH, C-C, C-O, and Si-O-Si groups [67,68].

An FTIR analysis of the individual polymers and their combination reveals how the unique chemical properties of each integrate into the mixture, thereby providing insight into their interactions and potential for use in specific applications.

### *4.5. Rheological Measurements*

An analysis of apparent viscosity as a function of shear rate was conducted for a 2% NaCl brine at 80 °C (Figure 7), representing the typical salinity conditions of the Hassi Messaoud reservoir. For the HPAM and mucilage solutions at concentrations of 1%, both exhibited quasi-Newtonian behaviors with viscosities of about 10 mPa·s. This behavior is consistent with that in other studies for HPAM solutions under comparable salinity conditions, highlighting the stability of low-concentration solutions [69,70].

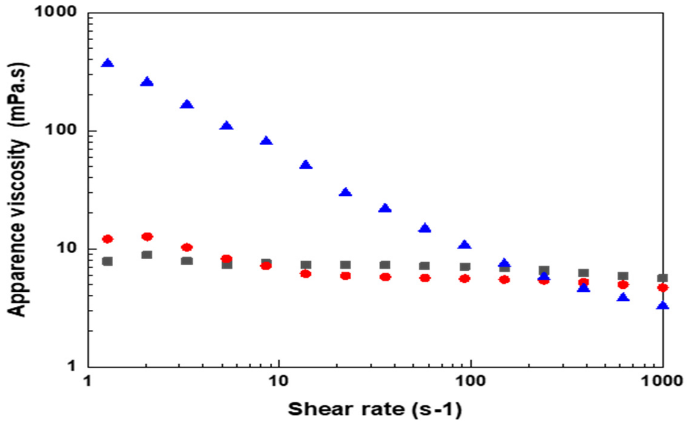


**Figure 7.** Flow curves for mucilage (black), HPAM (red), and mixed (blue) solutions.

However, the analysis of the mixture containing 80% HPAM and 20% mucilage at a total concentration of 10,000 ppm revealed a significant increase in viscosity, reaching approximately 1000 mPa·s. This observation aligns with those of previous research indicating that adding mucilage or other biopolymers to HPAM solutions can significantly enhance viscosity due to synergistic interactions. For example, studies have shown that incorporating silica into polymer systems can increase viscosity by strengthening the polymer network structure. Adding silica contributes to enhanced intermolecular interactions, resulting in higher viscosity, which is crucial for enhanced oil recovery applications.

The results from earlier works indicate that adding silica to HPAM and mucilage blends can improve their viscosity and increase the solutions' stability in saline environments [71,72]. For instance, one study demonstrated that incorporating silica into polymer systems increased their reactivity and resistance to salinity effects, thus allowing for better performance under reservoir conditions. These findings highlight the importance of synergies between components, where mucilage and silica could interact to offer even higher viscosity and optimized rheological characteristics.

This increase in viscosity is particularly relevant for enhanced oil recovery (EOR) applications. In the Hassi Messaoud reservoir context, higher viscosity can help reduce gravitational segregation and improve the mobility of the displacement fluid. Previous studies have also shown that more viscous fluids can better mobilize trapped oil in the pores, thereby increasing recovery efficiency.

In summary, the rheological results underscore the promising potential of the HPAM/mucilage mixture, especially when combined with additives such as silica in saline environments. These systems exhibit superior viscosity and flow characteristics compared with those of the individual solutions. This research contributes to understanding the rheology of polymer systems under specific reservoir conditions and opens avenues for optimizing oil recovery processes.

### *4.6. Core Flooding Analysis: Comparative Evaluation of HPAM, Opuntia ficus-indica, and Mixed Solutions for EOR*

This section presents the results of the analyses conducted during the core flooding experiments, including the relationship between pressure drop and flow rate for different polymer solutions. The fluid displacement curves, the SEM and EDX analyses of the plugs before and after injection, and the results of the XRD analysis are also discussed.

#### 4.6.1. Analysis of Pressure Drop and Volumetric Flow Rate for Different Polymer Solutions in Core Flooding

Studying the relationship between pressure drop (ΔP) and volumetric flow rate (Q) is critical for understanding polymer solutions' performance in core flooding experiments. These results provide an in-depth evaluation of the impact of each formulation on flow resistance, offering valuable insights into their behavior under simulated reservoir conditions. Particularly, Figure 8 presents the ΔP versus Q curves for the three types of solutions: HPAM, *Opuntia ficus-indica* cladode mucilage, and their blend. The figure explicitly shows discrete data points measured at injection rates of 0.5, 1, and 1.5 mL/min, with connecting lines added for clarity. Each solution was injected into a different core plug with similar petrophysical properties (permeability and porosity), and the system was reset between tests to ensure independent and reproducible results. These data establish a solid foundation for comparing the effectiveness of these formulations in enhanced oil recovery (EOR) processes, highlighting their potential to improve hydrocarbon displacement.

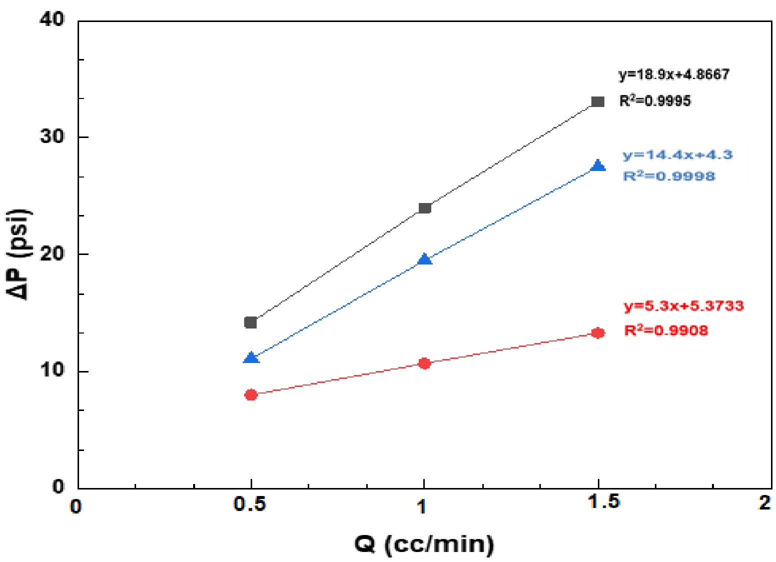


**Figure 8.** Drop pressure (ΔP) vs. flow rate (Q) for mucilage (red), HPAM (black), and mixed (blue) polymeric solutions in porous media.

The core flooding tests (Figure 8) revealed distinct performance differences among the three polymeric solutions: HPAM, *Opuntia ficus-indica* mucilage, and their blend. The HPAM solution exhibited the highest flow resistance, with a slope of 18.9, which is consistent with the findings from studies showing that high-viscosity HPAM can cause pore-blocking and lead to rapid pressure buildup, as reported by R. S. Seright et al. [73] and Guoyin Zhang [74]. This high resistance suggests that while HPAM can improve sweep efficiency, it may also reduce oil recovery due to increased formation damage.

In contrast, the *Opuntia ficus-indica* mucilage demonstrated a lower slope of 5.35, indicating reduced flow resistance. This result agrees with the results from recent research by Jae-Eun Ryou [75] and Hua Li [76], who found that natural polymers such as mucilage provide smoother flow through porous media due to their biocompatible structure. The observed lower pressure drop could enhance oil recovery by allowing more effortless movement through reservoir formations.

The HPAM/mucilage blend, with an intermediate slope of 14.4, strikes a balance between high mobility and low resistance, mitigating the risk of pore-clogging seen with pure HPAM. Similar results were documented in a study by Yan Liang [77], who demonstrated that blending HPAM with natural polymers such as xanthan gum can reduce viscosity-related clogging while maintaining enhanced recovery performance.

These results emphasize the importance of tailoring polymer formulations to manage viscosity and reduce formation damage in EOR processes. Integrating mucilage into HPAM formulations offers a promising solution, allowing for adjustable viscosities and reduced pressure drops. This could optimize EOR applications in saline reservoirs, such as in the Hassi Messaoud reservoir, where conditions require robust and adaptable solutions.

### 4.6.2. Analysis of Fluid Displacement Curves in Core Flooding

Figure 9 illustrates the relationship between differential pressure (DP) and injected pore volume (PV) for three polymeric solutions tested: HPAM, *Opuntia ficus-indica* mucilage, and their blend. This analysis provides valuable insights into the fluid dynamics within reservoir cores, shedding light on the mobility and efficiency of fluids under conditions representative of real oil reservoirs. Polymer injection in EOR processes often leads to increased differential pressure. This pressure is a key indicator of flow resistance and fluid mobility through the porous medium. Previous studies, such as those by Fuwei Yu [78], have shown that high-pressure drops associated with increased viscosity can hinder oil recovery due to pore blockage, a phenomenon observed with pure HPAM in our tests.

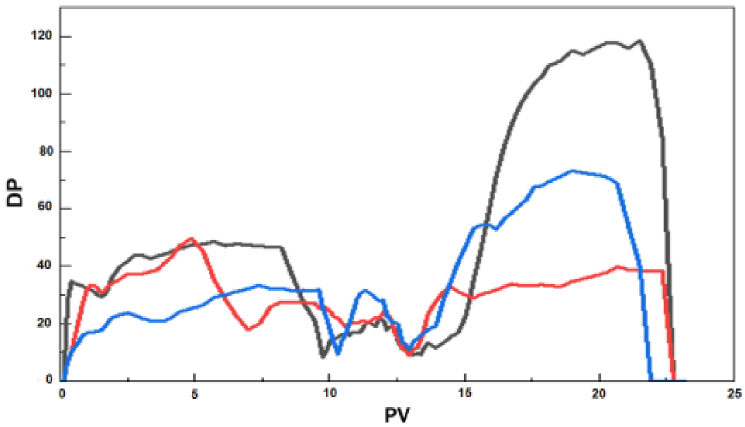


**Figure 9.** Variation in differential pressure (DP) as a function of injected volume (PV) for the mucilage (red), HPAM (black), and mixed (blue) polymeric solutions.

Our results show distinct differences among the tested solutions: the HPAM solution exhibited a high DP, increasing from 0 to 120 and stabilizing at a PV of 22.76, indicating significant flow resistance and potential blockage, which can impede oil recovery by slowing the advancement of the displacement front. In contrast, the *Opuntia ficus-indica* mucilage solution showed a much lower DP, ranging from 0 to 40, stabilizing at a PV of 23.1848, suggesting better fluid mobility and a more remarkable ability to recover hydrocarbons trapped in delicate pores. The HPAM/mucilage blend displayed an intermediate DP, reaching 80 at a PV of 21.92, offering a balanced compromise between flow resistance and fluid mobility, making it an efficient solution for enhanced oil recovery, as suggested by Laura M. Corredor [79] in their research on polymer formulations for high-salinity reservoir environments. At the end of the injection stage, the differential pressure (DP) decreased to zero for all polymeric solutions, despite the continued injection. This observation is indicative of the complete displacement of mobile oil within the core, as no further resistance to flow was observed. The disappearance of pressure drop suggests that the recovery process had reached its termination point, providing a rational criterion for halting the enhanced oil recovery operation.

These findings confirm that adding mucilage to HPAM improves EOR efficiency by reducing blockage while maintaining favorable fluid mobility [80,81].

The recovery factors varied significantly among the polymer solutions: the HPAM solution achieved a recovery factor of 63.3%, while the *Opuntia ficus-indica* mucilage alone achieved 84.35%. The HPAM/mucilage blend provided the highest recovery, reaching an impressive 94.28% recovery factor. These results, shown in Figure 10, emphasize the blend's superior performance in enhancing oil recovery compared with those of the individual polymer solutions, highlighting the potential benefits of combining synthetic and biopolymer solutions in EOR processes.

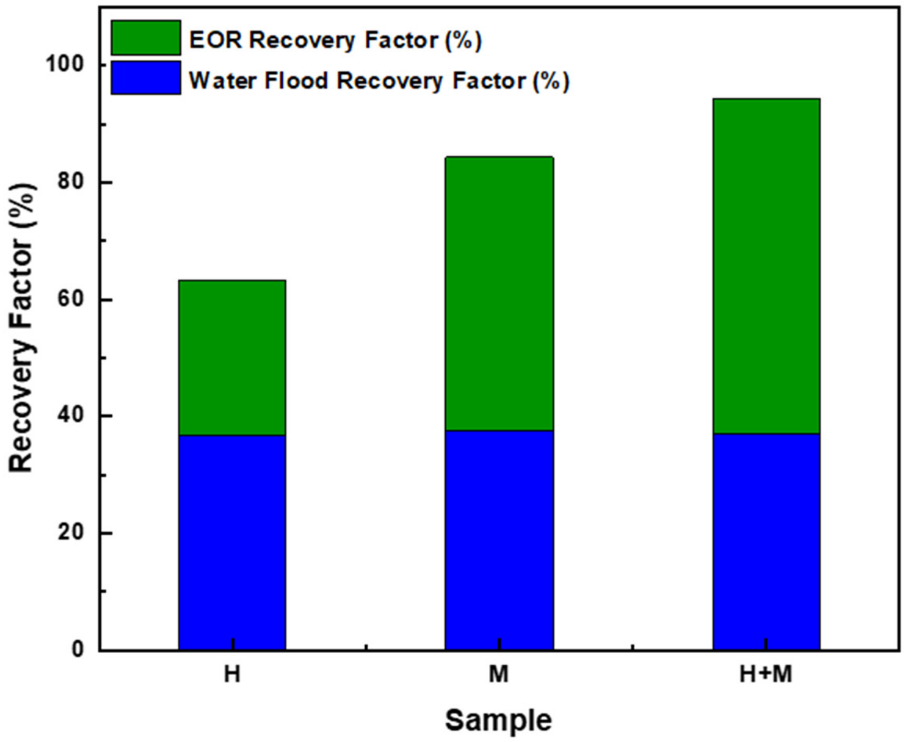


**Figure 10.** Comparison of recovery factors for mucilage (M), HPAM (H), and mixed (H+M) polymeric solutions.

#### 4.6.3. SEM and EDX Analysis of the Plugs Before and After Injection

The SEM/EDX analysis of the core plug samples before and after injection revealed significant changes in chemical composition, providing valuable insights into the interaction between the polymers and the core's pore matrix (Figure 11).

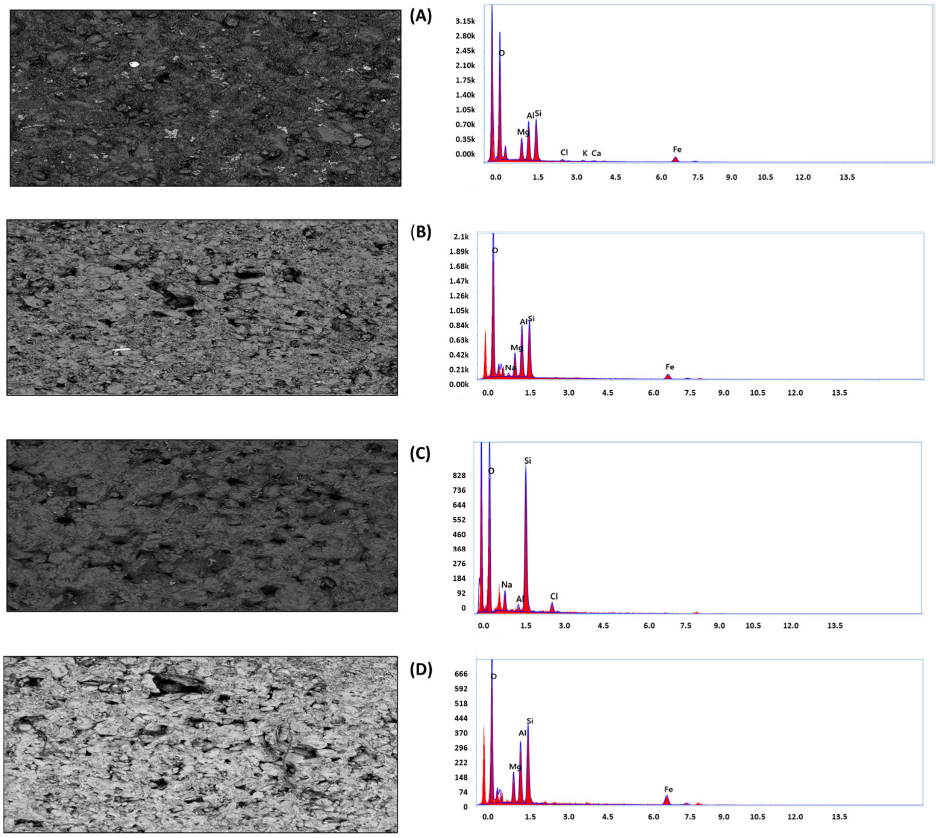


**Figure 11.** SEM/EDX (**A**): before injection; (**B**–**D**): after injection for Plug N°11(H)-12(M)-13(H+M)).

Pre-injection analyses showed that the plugs, sourced from a Triassic clay formation, contained elements such as oxygen (O), silicon (Si), magnesium (Mg), aluminum (Al), and iron (Fe), in agreement with the observations from YI Wayan Rakananda Saputra [82]. The prevalence of oxygen and silicon confirms the presence of silicate minerals, notably quartz. At the same time, magnesium and iron suggest the presence of clay minerals such as chlorites, consistent with the findings reported by Magda I. Youssif [83]. The elemental composition indicates the rocks' clayey and siliceous nature, which is essential for understanding the interactions during the injection of recovery fluids.

The post-injection results revealed notable characteristics. For Plug 11, the EDX analysis highlighted concentrations of sodium (Na), iron (Fe), magnesium (Mg), and silicon (Si) following the HPAM injection. The detection of sodium suggests ionic exchanges between the fluid and the rock minerals, an observation also reported by Imane Guetni [84]. The persistent concentrations of iron and magnesium in the rock underscore the stability of the minerals. At the same time, the limited pore openings indicate that the HPAM injection modestly altered the pore structure. These interactions may influence fluid mobility and the efficiency of the recovery process, as discussed in the work of Gordon M [85], which emphasizes that high-pressure losses can limit recovery.

For Plug 12, the SEM/EDX analysis of the polymer based on *Opuntia ficus-indica* cladodes showed a high concentration of silicon, along with oxygen (O), sodium (Na), aluminum (Al), and chlorine (Cl). The results indicate that this polymer promotes pore stability while enhancing fluid mobility, contrasting with conventional recovery fluids. Other studies, such as those by Yongqiang Bi [86], also report that natural polymers can reduce plugging, thereby improving recovery efficiency.

Finally, Plug 13 revealed significant characteristics following the injection of the HPAM and mucilage mixture. The predominant presence of silicon and other elements such as oxygen, magnesium, and iron demonstrated that the mixture optimizes pore structure management. This interaction is similar to that observed by Khalaf G. Salem [87], who found that polymeric mixtures can enhance recovery performance by facilitating fluid circulation. The results indicate that mucilage, combined with HPAM, provides considerable advantages for pore structure management, promoting faster oil recovery. In summary, this study highlights the importance of developing innovative polymer formulations that reduce undesirable interactions while enhancing the efficiency of enhanced oil recovery.

4.6.4. X-Ray Diffraction Analysis of Plugs Before and After Injection

To assess the mineralogical changes occurring in the plugs following the injection of various fluids, an X-ray diffraction (XRD) analysis was conducted (Figure 12). This technique allows for a comparative evaluation of the mineralogical composition of the plugs before and after treatment, providing crucial insights into the interactions between the injected fluids and the rock matrix. The results highlight potential structural and mineralogical changes that could influence the efficiency of enhanced oil recovery (EOR) processes.

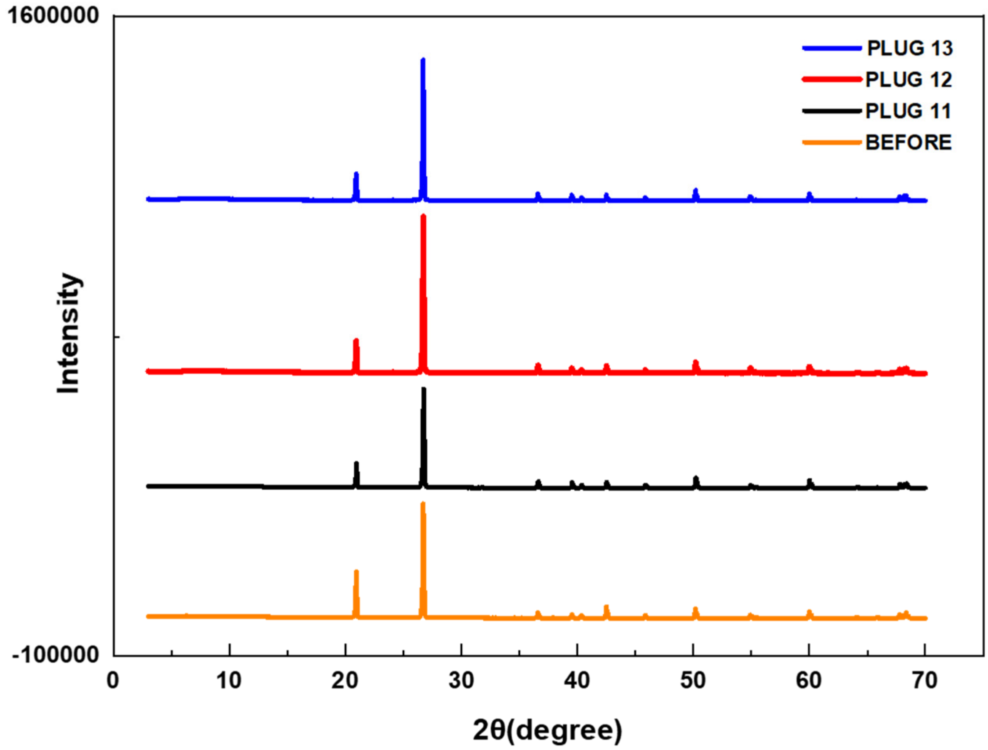


**Figure 12.** DRX (before injection; after injection: plug N°11(H)-12(M)-13(H+M)).

The pre-injection XRD analysis revealed that the reservoir plugs were primarily composed of quartz ($SiO_2$) and clinochlore-1M2b ((Mg, Fe), (Si, Al)$_4$O$_{10}$(OH)$_8$). These findings establish a stable baseline for evaluating mineralogical alterations induced by injecting different fluids.

Post-injection, the XRD results showed distinct variations based on the type of fluid used. For Plug 11, treated with HPAM, the XRD peaks remained relatively stable, indicating limited interaction with the rock and no significant mineralogical changes. This mineralogical stability aligns with the findings of Eseosa M. Ekanem [88], who reported similar stability in mineralogy when using synthetic polymers.

In contrast, Plugs 12 (mucilage) and 13 (mucilage–HPAM mixture) exhibited notable increases in the intensity of the XRD peaks after injection. This enhancement suggests increased crystallization or mineral reorganization within the rock pores, indicating a more pronounced interaction of mucilage-containing fluids with the rock minerals. These results align with the observations of Mohammed Bashir Abdullahi [89], who found that natural polymer fluids promote significant mineral reactivity and alteration compared with those of synthetic polymers. Plug 12, treated solely with mucilage, displayed more substantial modifications, corroborated by the SEM/EDX results indicating a more significant pore opening.

The pronounced mineral interactions facilitated by the mucilage contrast sharply with the relative stability observed with the HPAM, highlighting the advantages of biopolymer formulations in EOR. This finding supports the conclusions drawn by A. N. El-hoody [90], which emphasize the superior performance of natural polymers in enhancing oil recovery through improved mineral interactions.

## 5. Conclusions

This study demonstrated the potential of *Opuntia ficus-indica* cladode mucilage as a valuable alternative to conventional partially hydrolyzed polyacrylamides (HPAM) for enhanced oil recovery (EOR) applications. Thermal and spectroscopic analyses confirmed that both materials possess favorable physicochemical properties for EOR, with the blend exhibiting enhanced stability and interaction with the reservoir matrix.

XRD results highlighted the crystalline nature of the mucilage, contrasting with the amorphous structure of HPAM, suggesting distinct fluid-rock interaction behaviors. Core flooding experiments showed that the HPAM/mucilage blend achieved the highest oil recovery factor (94.28%) compared to HPAM alone (63.3%) and mucilage alone (84.35%), highlighting a strong synergistic effect.

Moreover, differential pressure analysis indicated that the blend maintained better flow characteristics and minimized pore blockage, leading to efficient oil displacement. SEM observations further confirmed improved pore structure and fluid mobility in plugs treated with mucilage-based solutions.

These results emphasize that integrating natural biopolymers like Opuntia mucilage can reduce the dependence on synthetic polymers, optimize oil recovery, and promote environmentally sustainable practices. Future work will involve testing this formulation on cores from other reservoirs and conducting field-scale validation to confirm its broad applicability.

**Author Contributions:** K.B. conceptualized this project, developed the methodology, coordinated all stages, managed the data, performed the formal analysis, and wrote the manuscript. A.E. conceptualized the material characterization methods, analyzed the test results, structured the manuscript, revised the manuscript, and contributed to the paper's publication via its APC. A.H. supervised the work and participated in revising the manuscript. C.E.I., M.F.A. and A.G. contributed to the implementation and methodology of the core flooding tests and injection experiments at DLCC SONATRACH. A.B. and A.I., as laboratory managers at DLCC SONATRACH, coordinated the experimental protocols. D.M. and M.B. guided the experiments and contributed to revisions of the manuscript. O.A.H. contributed to the supervision of the research work and the manuscript revision. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The data used in this article are available upon request by contacting the corresponding author.

**Conflicts of Interest:** Authors Charaf Eddine Izountar, Mohamed Fouad Abimouloud, Amin Bouhafs, Ammar Isseri and Djamila Maatalah were employed by the company Sonatrach. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References


1. Alvarado, V.; Manrique, E. Enhanced Oil Recovery: An Update Review. *Energies* **2010**, *3*, 1529–1575. [CrossRef]
2. Bello, A.; Ivanova, A.; Cheremisin, A. Foam EOR as an Optimization Technique for Gas EOR: A Comprehensive Review of Laboratory and Field Implementations. *Energies* **2023**, *16*, 972. [CrossRef]
3. Mahboob, A.; Kalam, S.; Kamal, M.S.; Hussain, S.M.S.; Solling, T. EOR Perspective of Microemulsions: A Review. *J. Pet. Sci. Eng.* **2022**, *208*, 109312. [CrossRef]
4. Mogensen, K.; Masalmeh, S. A Review of EOR Techniques for Carbonate Reservoirs in Challenging Geological Settings. *J. Pet. Sci. Eng.* **2020**, *195*, 107889. [CrossRef]
5. Malozyomov, B.V.; Martyushev, N.V.; Kukartsev, V.V.; Tynchenko, V.S.; Bukhtoyarov, V.V.; Wu, X.; Tyncheko, Y.A.; Kukartsev, V.A. Overview of Methods for Enhanced Oil Recovery from Conventional and Unconventional Reservoirs. *Energies* **2023**, *16*, 4907. [CrossRef]
6. Kang, W.-L.; Zhou, B.-B.; Issakhov, M.; Gabdullin, M. Advances in Enhanced Oil Recovery Technologies for Low Permeability Reservoirs. *Pet. Sci.* **2022**, *19*, 1622–1640. [CrossRef]
7. Davoodi, S.; Al-Shargabi, M.; Wood, D.A.; Rukavishnikov, V.S.; Minaev, K.M. Experimental and Field Applications of Nanotechnology for Enhanced Oil Recovery Purposes: A Review. *Fuel* **2022**, *324*, 124669. [CrossRef]
8. Xu, Z.-X.; Li, S.-Y.; Li, B.-F.; Chen, D.-Q.; Liu, Z.-Y.; Li, Z.-M. A Review of Development Methods and EOR Technologies for Carbonate Reservoirs. *Pet. Sci.* **2020**, *17*, 990–1013. [CrossRef]
9. Liu, X.; Lai, J.; Fan, X.; Shu, H.; Wang, G.; Ma, X.; Liu, M.; Guan, M.; Luo, Y. Insights in the Pore Structure, Fluid Mobility and Oiliness in Oil Shales of Paleogene Funing Formation in Subei Basin, China. *Mar. Pet. Geol.* **2020**, *114*, 104228. [CrossRef]
10. Guetni, I.; Marlière, C.; Rousseau, D.; Pelletier, M.; Bihannic, I.; Villiéras, F. Transport of EOR Polymer Solutions in Low Permeability Porous Media: Impact of Clay Type and Injection Water Composition. *J. Pet. Sci. Eng.* **2020**, *186*, 106690. [CrossRef]
11. Jiang, W.; Hou, Z.; Wu, X.; Song, K.; Yang, E.; Huang, B.; Dong, C.; Lu, S.; Sun, L.; Gai, J.; et al. A New Method for Calculating the Relative Permeability Curve of Polymer Flooding Based on the Viscosity Variation Law of Polymer Transporting in Porous Media. *Molecules* **2022**, *27*, 3958. [CrossRef] [PubMed]
12. Liao, H.; Yu, H.; Xu, G.; Liu, P.; He, Y.; Zhou, Y. Polymer-Surfactant Flooding in Low-Permeability Reservoirs: An Experimental Study. *ACS Omega* **2022**, *7*, 4595–4605. [CrossRef] [PubMed]
13. Guo, H.; Song, K.; Hilfer, R. A Critical Review of Capillary Number and Its Application in Enhanced Oil Recovery. In Proceedings of the SPE Improved Oil Recovery Conference, Virtual, 31 August–4 September 2020.
14. Zhang, J.; Wang, S.; Wang, X.; Huang, B.; Zuo, M.; Chen, H. The Influence Mechanism and the Contribution of Capillary Force and Gravity to Recovery in Spontaneous Imbibition in Low Permeability Reservoirs. *J. Dispers. Sci. Technol.* **2024**, *45*, 720–730. [CrossRef]
15. Zhang, Y.; Wang, Y.; Gao, J.; Cui, Y.; Wang, S. Study of the Influence of Dynamic and Static Capillary Forces on Production in Low-Permeability Reservoirs. *Energies* **2023**, *16*, 1554. [CrossRef]
16. Gao, W.; Tang, X.; Xu, M.; Li, Y.; Zhong, Y.; Kong, D.; Wen, Y.; Li, Q. Surfactant–Polymer Viscosity Effects on Enhanced Oil Recovery Across Pore Structures: Microfluidic Insights from Pore Scale to Darcy Scale. *Energy Fuels* **2024**, *38*, 17380–17391. [CrossRef]
17. Rezaei, A.; Abdollahi, H.; Derikvand, Z.; Hemmati-Sarapardeh, A.; Mosavi, A.; Nabipour, N. Insights into the Effects of Pore Size Distribution on the Flowing Behavior of Carbonate Rocks: Linking a Nano-Based Enhanced Oil Recovery Method to Rock Typing. *Nanomaterials* **2020**, *10*, 972. [CrossRef]
18. Kalam, S.; Abu-Khamsin, S.A.; Kamal, M.S.; Patil, S. A Review on Surfactant Retention on Rocks: Mechanisms, Measurements, and Influencing Factors. *Fuel* **2021**, *293*, 120459. [CrossRef]
19. Mushtaq, M.; Al-Shalabi, E.W.; AlAmeri, W. A Review on Retention of Surfactants in Enhanced Oil Recovery: A Mechanistic Insight. *Geoenergy Sci. Eng.* **2023**, *230*, 212243. [CrossRef]
20. Salam, A.H.; Alsaif, B.; Hussain, S.M.S.; Khan, S.; Kamal, M.S.; Patil, S.; Al-Shalabi, E.W.; Hassan, A.M. Advances in Understanding Polymer Retention in Reservoir Rocks: A Comprehensive Review. *Polym. Rev.* **2024**, *64*, 1387–1413. [CrossRef]
21. Al-shalabi, E.W. Effects of Trapping Number on Biopolymer Flooding Recovery of Carbonate Reservoirs. *Pet. Explor. Dev.* **2022**, *49*, 895–905. [CrossRef]
22. Beteta, A.; McIver, K.; Vazquez, O.; Boak, L.; Jordan, M.; Shields, R. The Impact of EOR Polymers on Scale Inhibitor Adsorption. In Proceedings of the SPE Virtual International Oilfield Scale Conference and Exhibition 2020, Virtual, 24–25 June 2020. [CrossRef]
23. Belhaj, A.; Elraies, K.; Sarma, H.; Muhamad Shuhili, J.A.; Mahmood, S.; Alnarabiji, M. Surfactant Partitioning and Adsorption in Chemical EOR: The Neglected Phenomenon in Porous Media. In Proceedings of the SPE/IATMI Asia Pacific Oil & Gas Conference and Exhibition, Virtual, 12–14 October 2021.
24. Skauge, A.; Zamani, N.; Gausdal Jacobsen, J.; Shaker Shiran, B.; Al-Shakry, B.; Skauge, T. Polymer Flow in Porous Media: Relevance to Enhanced Oil Recovery. *Colloids Interfaces* **2018**, *2*, 27. [CrossRef]

25. Cancela, B.R.; Palermo, L.C.M.; de Oliveira, P.F.; Mansur, C.R.E. Rheological Study of Polymeric Fluids Based on HPAM and Fillers for Application in EOR. *Fuel* **2022**, *330*, 125647. [CrossRef]
26. Du, Y.; Zhu, Y.; Ji, Y.; Xu, H.; Zhang, H.; Yuan, S. Effect of Salt-Resistant Monomers on Viscosity of Modified Polymers Based on the Hydrolyzed Poly-Acrylamide (HPAM): A Molecular Dynamics Study. *J. Mol. Liq.* **2021**, *325*, 115161. [CrossRef]
27. Kang, P.-S.; Lim, J.-S.; Huh, C. Temperature Dependence of the Shear-Thinning Behavior o Partially Hydrolyzed Polyacrylamide Solution for Enhanced Oil Recovery. *J. Energy Resour. Technol.* **2020**, *143*, 063002. [CrossRef]
28. Santos, J.F.; Santos, A.S.; de Oliveira, P.F.; Santos, I.C.V.M.; Mansur, C.R.E. Statistical and Rheological Evaluation of the Effect of Salts in Partially Hydrolyzed Polyacrylamide Solutions. *J. Appl. Polym. Sci.* **2024**, *141*, e55278. [CrossRef]
29. Fu, X.; Qin, F.; Liu, T.; Zhang, X. Enhanced Oil Recovery Performance and Solution Properties of Hydrophobic Associative Xanthan Gum. *Energy Fuels* **2022**, *36*, 181–194. [CrossRef]
30. Navaie, F.; Esmaeilnezhad, E.; Jin Choi, H. Xanthan Gum-Added Natural Surfactant Solution of Chuback: A Green and Clean Technique for Enhanced Oil Recovery. *J. Mol. Liq.* **2022**, *354*, 118909. [CrossRef]
31. Elsaeed, S.M.; Zaki, E.G.; Omar, W.A.E.; Ashraf Soliman, A.; Attia, A.M. Guar Gum-Based Hydrogels as Potent Green Polymers for Enhanced Oil Recovery in High-Salinity Reservoirs. *ACS Omega* **2021**, *6*, 23421–23431. [CrossRef]
32. Said, M.; Haq, B.; Al Shehri, D.; Rahman, M.M.; Muhammed, N.S.; Mahmoud, M. Modification of Xanthan Gum for a High-Temperature and High-Salinity Reservoir. *Polymers* **2021**, *13*, 4212. [CrossRef]
33. Sayyouh, M.H.; Al-Blehed, M. Screening Criteria for Enhanced Recovery of Saudi Crude OUs. *Energy Sources* **1990**, *12*, 71–82. [CrossRef]
34. Melo, M.A.; Lins, A.G.; Silva, I.P. Lessons Learned From Polymer Flooding Pilots in Brazil. In Proceedings of the SPE Latin America and Caribbean Mature Fields Symposium, Salvador, Bahia, Brazil, 15–16 March 2017.
35. Shuker, M.T.; Buriro, M.A.; Hamza, M.M. Enhanced Oil Recovery: A Future for Pakistan. In Proceedings of the SPE/PAPG Annual Technical Conference, Islamabad, Pakistan, 3–5 December 2012.
36. Helmi, M.E.; Abu El Ela, M.; Desouky, S.M.; Sayyouh, M.H. Effects of Nanocomposite Polymer Flooding on Egyptian Crude Oil Recovery. *J. Petrol. Explor. Prod. Technol.* **2020**, *10*, 3937–3945. [CrossRef]
37. Ali, H.A.; Musa, T.A.; Doroudi, A. Chemical Enhanced Oil Recovery Pilot Design for Heglig Main Field-Sudan. In Proceedings of the SPE Saudi Arabia Section Annual Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia, 21–23 April 2015; SPE-177984-MS. [CrossRef]
38. Gutierrez, M.; Castro, R.H.; Corredor, L.M.; Fernández, F.R.; Zapata, J.; Jimenez, J.A.; Reyes, J.D.; Rojas, D.M.; Jimenez, R.; Acosta, T.; et al. Chemical Enhanced Oil Recovery Experiences in Colombia: Field Pilots Review. In Proceedings of the SPE Improved Oil Recovery Conference, Tulsa, OK, USA, 22–25 April 2024; D031S019R003. [CrossRef]
39. Zhang, X.; Han, M.; Fuseni, A.; Alsofi, A.M. An Approach to Evaluate Polyacrylamide-Type Polymers' Long-Term Stability under High Temperature and High Salinity Environment. *J. Pet. Sci. Eng.* **2019**, *180*, 518–525. [CrossRef]
40. Zhang, L.; Khan, N.; Pu, C. A New Method of Plugging the Fracture to Enhance Oil Production for Fractured Oil Reservoir Using Gel Particles and the HPAM/Cr3+ System. *Polymers* **2019**, *11*, 446. [CrossRef] [PubMed]
41. Wang, B.; Lin, M.; Guo, J.; Wang, D.; Xu, F.; Li, M. Plugging Properties and Profile Control Effects of Crosslinked Polyacrylamide Microspheres. *J. Appl. Polym. Sci.* **2016**, *133*. [CrossRef]
42. Guo, H. How to Select Polymer Molecular Weight and Concentration to Avoid Blocking in Polymer Flooding? In Proceedings of the SPE Symposium: Production Enhancement and Cost Optimisation, Kuala Lumpur, Malaysia, 7–8 November 2017.
43. Wu, H.; Ge, J.; Yang, L.; Yang, Y.; Zhang, T.; Guo, H. Developments of Polymer Gel Plug for Temporary Blocking in SAGD Wells. *J. Pet. Sci. Eng.* **2022**, *208*, 109650. [CrossRef]
44. Ekunke, V.; Kosi, S.; Junior, J.; Obada, O.; Ikechukwu, S.; Ifechukwu, J.; Collins, I.; Chadi, P.; Ibe, M.; Peter, Y. Enhanced Oil Recovery Methods Using Biodegradable Materials in Different Reservoirs. *Glob. Sci. J.* **2024**, *12*, 647–664.
45. Haq, B.; Liu, J.; Liu, K.; Al Shehri, D. The Role of Biodegradable Surfactant in Microbial Enhanced Oil Recovery. *J. Pet. Sci. Eng.* **2020**, *189*, 106688. [CrossRef]
46. Barba, F.J.; Garcia, C.; Fessard, A.; Munekata, P.E.S.; Lorenzo, J.M.; Aboudia, A.; Ouadia, A.; Remize, F. Opuntia Ficus Indica Edible Parts: A Food and Nutritional Security Perspective. *Food Rev. Int.* **2022**, *38*, 930–952. [CrossRef]
47. Ribeiro, R.C.d.A.; Barreto, S.M.d.A.G.; Ostrosky, E.A.; da Rocha-Filho, P.A.; Veríssimo, L.M.; Ferrari, M. Production and Characterization of Cosmetic Nanoemulsions Containing *Opuntia ficus-indica* (L.) Mill Extract as Moisturizing Agent. *Molecules* **2015**, *20*, 2492–2509. [CrossRef]
48. Bayar, N.; Kriaa, M.; Kammoun, R. Extraction and Characterization of Three Polysaccharides Extracted from Opuntia Ficus Indica Cladodes. *Int. J. Biol. Macromol.* **2016**, *92*, 441–450. [CrossRef]
49. Quinzio, C.; Ayunta, C.; Alancay, M.; de Mishima, B.L.; Iturriaga, L. Physicochemical and Rheological Properties of Mucilage Extracted from *Opuntia Ficus Indica* (L. Miller). Comparative Study with Guar Gum and Xanthan Gum. *Food Meas.* **2018**, *12*, 459–470. [CrossRef]

50. Medina-Torres, L.; Brito-De La Fuente, E.; Torrestiana-Sanchez, B.; Katthain, R. Rheological Properties of the Mucilage Gum (*Opuntia Ficus Indica*). *Food Hydrocoll.* **2000**, *14*, 417–424. [CrossRef]
51. Bourkaib, K.; Hadjsadok, A.; Djedri, S. Synergistic Effect of *Opuntia ficus-indica* Cladode Mucilage on Physicochemical and Rheological Properties of HPAM Polymer Solutions for EOR Application. *Colloids Surf. A Physicochem. Eng. Asp.* **2024**, *691*, 133794. [CrossRef]
52. Andrade, L.A.; Nunes, C.A.; Pereira, J. Physical and Chemical Analysis in Crude Taro Mucilage Obtained by Simple Extraction Technique. *Bol. Cent. Pesqui. Process. Aliment.* **2019**, *37*. [CrossRef]
53. Otálora, M.C.; Gómez Castaño, J.A.; Wilches-Torres, A. Preparation, Study and Characterization of Complex Coacervates Formed between Gelatin and Cactus Mucilage Extracted from Cladodes of *Opuntia ficus-indica*. *LWT* **2019**, *112*, 108234. [CrossRef]
54. Otálora, M.C.; Carriazo, J.G.; Iturriaga, L.; Nazareno, M.A.; Osorio, C. Microencapsulation of Betalains Obtained from Cactus Fruit (*Opuntia ficus-indica*) by Spray Drying Using Cactus Cladode Mucilage and Maltodextrin as Encapsulating Agents. *Food Chem.* **2015**, *187*, 174–181. [CrossRef]
55. Manhivi, V.E.; Venter, S.; Amonsou, E.O.; Kudanga, T. Composition, Thermal and Rheological Properties of Polysaccharides from Amadumbe (*Colocasia Esculenta*) and Cactus (*Opuntia* Spp.). *Carbohydr. Polym.* **2018**, *195*, 163–169. [CrossRef]
56. Otálora, M.C.; Wilches-Torres, A.; Castaño, J.A.G. Extraction and Physicochemical Characterization of Dried Powder Mucilage from *Opuntia ficus-indica* Cladodes and Aloe Vera Leaves: A Comparative Study. *Polymers* **2021**, *13*, 1689. [CrossRef]
57. Maurer, J.J.; Schulz, D.N.; Siano, D.B.; Bock, J. Thermal Analysis of Acrylamide-Based Polymers. In *Analytical Calorimetry*; Johnson, J.F., Gill, P.S., Eds.; Springer: Boston, MA, USA, 1984; Volume 5, pp. 43–55. ISBN 978-1-4613-2699-1.
58. Neamtu, I.; Chiriac, A.P.; Nita, L.E. Characterization of Poly(Acrylamide) as Temperature- Sensitive Hydrogel. *J. Optoelectron. Adv. Mater.* **2006**, 8.
59. Olajire, A.A. Review of ASP EOR (Alkaline Surfactant Polymer Enhanced Oil Recovery) Technology in the Petroleum Industry: Prospects and Challenges. *Energy* **2014**, *77*, 963–982. [CrossRef]
60. Ouhammou, M.; Nabil, B.; Hidar, N.; Ouaabou, R.; Bouchdoug, M.; Jaouad, A.; Mahrouz, M. Chemical Activation of the Skin of Prickly Pear Fruits and Cladode *Opuntia Megacantha: Treatment* of Textile Liquid Discharges. *S. Afr. J. Chem. Eng.* **2021**, *37*, 118–126. [CrossRef]
61. Sosa-Fernandez, P.A.; Miedema, S.J.; Bruning, H.; Leermakers, F.A.M.; Rijnaarts, H.H.M.; Post, J.W. Influence of Solution Composition on Fouling of Anion Exchange Membranes Desalinating Polymer-Flooding Produced Water. *J. Colloid Interface Sci.* **2019**, *557*, 381–394. [CrossRef] [PubMed]
62. Benhamou, A.; Boussetta, A.; Grimi, N.; Idrissi, M.E.; Nadifiyine, M.; Barba, F.J.; Moubarik, A. Characteristics of Cellulose Fibers from Opuntia Ficus Indica Cladodes and Its Use as Reinforcement for PET Based Composites. *J. Nat. Fibers* **2022**, *19*, 6148–6164. [CrossRef]
63. Contreras-Padilla, M.; Rivera-Muñoz, E.M.; Gutiérrez-Cortez, E.; del López, A.R.; Rodríguez-García, M.E. Characterization of Crystalline Structures in *Opuntia ficus-indica*. *J. Biol. Phys.* **2015**, *41*, 99–112. [CrossRef]
64. Bao, M.; Chen, Q.; Li, Y.; Jiang, G. Biodegradation of Partially Hydrolyzed Polyacrylamide by Bacteria Isolated from Production Water after Polymer Flooding in an Oil Field. *J. Hazard. Mater.* **2010**, *184*, 105–110. [CrossRef]
65. Haruna, M.A.; Pervaiz, S.; Hu, Z.; Nourafkan, E.; Wen, D. Improved Rheology and High-Temperature Stability of Hydrolyzed Polyacrylamide Using Graphene Oxide Nanosheet. *J. Appl. Polym. Sci.* **2019**, *136*, 47582. [CrossRef]
66. Monje, P.V.; Baran, E.J. Complex Biomineralization Pattern in Cactaceae. *J. Plant Physiol.* **2004**, *161*, 121–123. [CrossRef]
67. Azli, N.B.; Junin, R.; Agi, A.A.; Risal, A.R. Partially Hydrolyzed Polyacrylamide Apparent Viscosity in Porous Media Enhancement by Silica Dioxide Nanoparticles under High Temperature and High Salinity. *J. Appl. Sci. Eng.* **2021**, *25*, 581–593. [CrossRef]
68. Magami, S.; Haruna, M. Influence of Nanoparticle Size Distributions on the (in)Stability and Rheology of Colloidal $SiO_2$ Dispersions and HPAM/SiO2 Nanofluid Hybrids. *Fine Chem. Eng.* **2023**, *4*, 257–270. [CrossRef]
69. Cardenas, A.; Higuera-Ciapara, I.; Goycoolea, F. Rheology and Aggregation of Cactus (*Opuntia ficus-indica* ) Mucilage in Solution. *J. Prof. Assoc. Cactus Dev.* **1997**, *2*, 152–159.
70. Freitas Lopes, L.; Silveira, B.; Moreno, R. Rheological Evaluation of HPAM Fluids for EOR Applications. *Int. J. Eng. Technol. IJET-IJENS* **2014**, *14*, 35–41.
71. Corredor, L.; Maini, B.; Husein, M. Improving Polymer Flooding by Addition of Surface Modified Nanoparticles. In Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition, Brisbane, Australia, 23–25 October 2018.
72. Wang, Y.; He, Z.; Chen, W.; Liu, Y.; Ding, M.; Yang, Z.; Qian, C. Stability and Rheological Properties of HPAM/Nanosilica Suspensions: Impact of Salinity. *Colloids Surf. A Physicochem. Eng. Asp.* **2020**, *587*, 124320. [CrossRef]
73. Seright, R.S.; Seheult, M.; Talashek, T. Injectivity Characteristics of EOR Polymers. *SPE Reserv. Eval. Eng.* **2009**, *12*, 783–792. [CrossRef]
74. Zhang, G.; Seright, R. Hydrodynamic Retention and Rheology of EOR Polymers in Porous Media. *Proc.—SPE Int. Symp. Oilfield Chem.* **2015**, *1*, 266–280. [CrossRef]

75. Ryou, J.-E.; Jung, J. Characteristics of Thermo-Gelation Biopolymer Solution Injection into Porous Media. *Constr. Build. Mater.* **2023**, *384*, 131451. [CrossRef]
76. Li, H.; Zhu, W.; Niu, H.; Gao, Y.; Chen, Z.; Song, Z.; Kong, D. 2-D Porous Flow Field Reveals Different EOR Mechanisms between the Biopolymer and Chemical Polymer. *J. Pet. Sci. Eng.* **2022**, *210*, 110084. [CrossRef]
77. Liang, Y.; Wang, Z.; Jin, Y.; Tian, Y.; Liu, X.; Guo, Y.; Fan, L.; Wang, J.; Zhang, X.; Cao, M.; et al. Heterogeneity Control Ability in Porous Media: Associative Polymer versus HPAM. *J. Pet. Sci. Eng.* **2019**, *183*, 106425. [CrossRef]
78. Imaddahen, A. Étude Expérimentale Multi-Échelle et Modélisation Hybride Prédictive Du Comportement, de L'endommagement et de La Durée de Vie En Fatigue d'un Matériau Composite Polypropylène/Fibres de Verre. Ph.D. Thesis, HESAM Université, Paris, France, 2020.
79. Corredor, L.M.; Aliabadian, E.; Husein, M.; Chen, Z.; Maini, B.; Sundararaj, U. Heavy Oil Recovery by Surface Modified Silica Nanoparticle/HPAM Nanofluids. *Fuel* **2019**, *252*, 622–634. [CrossRef]
80. Lai, N.; Tang, L.; Jia, N.; Qiao, D.; Chen, J.; Wang, Y.; Zhao, X. Feasibility Study of Applying Modified Nano-$SiO_2$ Hyperbranched Copolymers for Enhanced Oil Recovery in Low-Mid Permeability Reservoirs. *Polymers* **2019**, *11*, 1483. [CrossRef]
81. Long, Y.; Wang, R.; Zhu, B.; Huang, X.; Leng, Z.; Chen, L.; Song, F. Enhanced Oil Recovery by a Suspension of Core-Shell Polymeric Nanoparticles in Heterogeneous Low-Permeability Oil Reservoirs. *Nanomaterials* **2019**, *9*, 600. [CrossRef]
82. Saputra, I.W.R.; Adebisi, O.; Ladan, E.B.; Bagareddy, A.; Sarmah, A.; Schechter, D.S. The Influence of Oil Composition, Rock Mineralogy, Aging Time, and Brine Pre-Soak on Shale Wettability. *ACS Omega* **2022**, *7*, 85–100. [CrossRef] [PubMed]
83. Youssif, M.I.; El-Maghraby, R.M.; Saleh, S.M.; Elgibaly, A. Silica Nanofluid Flooding for Enhanced Oil Recovery in Sandstone Rocks. *Egypt. J. Pet.* **2018**, *27*, 105–110. [CrossRef]
84. Guetni, I.; Marliere, C.; Rousseau, D.; Bihannic, I.; Pelletier, M.; Villieras, F. Transport of HPAM Solutions in Low Permeability Porous Media: Impacts of Salinity and Clay Content. In Proceedings of the SPE Europec featured at 81st EAGE Conference and Exhibition, London, UK, 3–6 June 2019; p. D041S011R001. [CrossRef]
85. Graham, G.M.; Frigo, D.M. Production Chemistry Issues and Solutions Associated with Chemical EOR. In Proceedings of the SPE International Conference on Oilfield Chemistry, Galveston, TX, USA, 8–9 April 2019; p. D021S008R001. [CrossRef]
86. Bi, Y.; Xiu, J.; Ma, T. Application Potential Analysis of Enhanced Oil Recovery by Biopolymer-Producing Bacteria and Biosurfactant-Producing Bacteria Compound Flooding. *Appl. Sci.* **2019**, *9*, 5119. [CrossRef]
87. Salem, K.G.; Salem, A.M.; Tantawy, M.A.; Gawish, A.A.; Gomaa, S.; El-hoshoudy, A.N. A Comprehensive Investigation of Nanocomposite Polymer Flooding at Reservoir Conditions: New Insights into Enhanced Oil Recovery. *J. Polym. Environ.* **2024**, *32*, 5915–5935. [CrossRef]
88. Ekanem, E.M.; Rücker, M.; Yesufu-Rufai, S.; Spurin, C.; Ooi, N.; Georgiadis, A.; Berg, S.; Luckham, P.F. Novel Adsorption Mechanisms Identified for Polymer Retention in Carbonate Rocks. *JCIS Open* **2021**, *4*, 100026. [CrossRef]
89. Bashir Abdullahi, M.; Rajaei, K.; Junin, R.; Bayat, A.E. Appraising the Impact of Metal-Oxide Nanoparticles on Rheological Properties of HPAM in Different Electrolyte Solutions for Enhanced Oil Recovery. *J. Pet. Sci. Eng.* **2019**, *172*, 1057–1068. [CrossRef]
90. El-hoshoudy, A.N. Experimental and Theoretical Investigation for Synthetic Polymers, Biopolymers and Polymeric Nanocomposites Application in Enhanced Oil Recovery Operations. *Arab. J. Sci. Eng.* **2022**, *47*, 10887–10915. [CrossRef]