New insights into guar gum as environmentally friendly polymer for enhanced oil recovery in high-salinity and high-temperature sandstone reservoirs

Tagwa A. Musa1,2 · Ahmed F. Ibrahim3 · Hisham A. Nasr-El-Din3 · Anas. M. Hassan4

Received: 9 August 2020 / Accepted: 26 December 2020 / Published online: 1 February 2021
© The Author(s) 2021

Abstract
Chemical enhanced oil recovery (EOR) processes are usually used as additives for hydrocarbon production due to its simplicity and relatively reasonable additional production costs. Polymer flooding uses polymer solutions to increase oil recovery by decreasing the water/oil mobility ratio by increasing the viscosity of the displacing water. The commonly used synthetic water-soluble polymer in EOR application is partially hydrolyzed polyacrylamide (HPAM). However, synthetic polymers in general are not attractive because of high cost, environmental concerns, limitation in high temperature, and high-salinity environment. Guar gum is an environmentally friendly natural water-soluble polymer available in large quantities in many countries and widely used in various applications in the oil and gas industry especially in drilling fluids and hydraulic fracturing operations; however, very limited studies investigated on guar as a polymer for EOR and no any study investigated on its uses in high-temperature and high-salinity reservoirs. The objective of this study is to confirm the use of guar gum as a natural polymer for EOR applications in sandstone reservoirs and investigate its applicability for high-temperature and high-salinity reservoirs. The study experimentally investigated rheological characteristics of a natural polymer obtained from guar gum with consideration of high temperature (up to 210 °F) and high salinity (up to 20% NaCl) and tested the guar solution as EOR polymer. The results of this study show that the guar solution can be used as an environmentally friendly polymer to enhance oil recovery. Based on the results, it can be concluded that guar gum shows shear-thinning behavior and strongly susceptible to microbial degradation but also shows a very good properties stability in high temperature and salinity, where in low shear rate case, about 100 cp viscosity can be achieved at 210 °F for polymer prepared in deionized water. Guar polymer shows good viscosity in the presence of 20% NaCl where the viscosity is acceptable for temperature less than 190 °F. Also, the flooding experiment shows that the recovery factor can be increased by 16%.

Keywords Guar gum · Chemical EOR (chemical EOR) · Polymer-flooding · High salinity · High temperature · Sandstone reservoirs

Introduction
Chemical EOR techniques are usually used as additives for hydrocarbon production due to its simplicity and relatively reasonable additional production costs (Wang 2003; Sheng 2010; Olajire 2014; Hassan et al. 2017 and 2019). Alkali–surfactant–polymer and polymer are the common flooding systems used in chemical EOR operations (Sweis-trup et al. 2016; Gao et al. 1995; Hou et al. 2005; James 2013; Kang et al. 2000). Polymer flooding is an EOR method that uses polymer solutions to increase oil recovery by decreasing the water/oil mobility ratio by increasing the viscosity of the displacing water. As a result, the oil recovery and the sweep efficiency improve (Wolfgang
Water-soluble polymers are widely used in petroleum field operations like well-drilling, hydraulic fracturing fluids, and EOR processes (Huggins 1942; Nasr-El-Din and Noy 1992; Wei Yu et al. 2014; Andrew et al. 2016; Almansour et al. 2017; Lee and Lee 2019). Partially hydrolyzed polyacrylamide (HPAM) is the most extensively implemented synthetic water-soluble polymer used in EOR applications (Sveistrup et al. 2016; Wang 2018). However, the synthetic polymers as general are not attractive because of high cost, environmental concerns, limitation in high salinity, and limitation in high temperature (Samanta et al. 2011; Mohammadi et al. 2012; Shiran and Skauge 2013). Researchers are always working to find suitable natural polymer to solve these problems. Guar gum is an environmentally friendly natural polymer applicable as a candidate for EOR applications, which is available in a huge amount in Pakistan and India, with a great quantity in the USA, Sudan, Australia, and Brazil (OEPA 2015; Hassan et al. 2019a, b). Guar plant tolerates different types of soil ranging from sandy to heavy clay soil (Hymowitz 1979). Guar gum is a seed endosperm portion gained from the cluster bean herbal. It generally comprises of high molecular weight polysaccharides of galactomannans ranges between 0.1 and 2.8 million which are a linear chain of (1 \rightarrow 4)-linked \beta-D-mannopyranosyl units with (1 \rightarrow 6)-linked \alpha-D-galactopyranosyl remains as side chains (Mudgil et al. 2014). Guar gum is solvable in cold water without heating, but it is insolvable in organic solvents. High viscous solution can be made depending on the guar concentration. The efficiency of polymer solutions highly depends on its rheological properties (Nasr-El-Din et al. 1991; Taylor et al. 1998; Airey 2003; Kim et al. 2010; Jang et al. 2015).

Guar gum is widely used in various applications in the petroleum industry. For example, Guar gum is used in drilling fluids and hydraulic fracturing operations; however, its applications in EOR are still limited. Few experimental works investigated the use of guar gum as a polymer in alkaline surfactant polymer (ASP) flooding for reservoir temperatures less than 50 °C and for very low salinity (Mohd et al. 2018). However, to date, there is no comprehensive investigational study for the use of guar gum as a polymer for enhancing oil recovery under high specific salinity and temperature environments.

This study experimentally investigated rheological properties of a natural polymer obtained from guar gum and salinity brine with consideration of high salinity and high temperature (20% NaCl and 210 °F), respectively, and tested the guar gum solution as promising EOR polymer in sandstone reservoirs.

### Experimental studies

#### Materials

Guar gum was used as a natural polymer in all the experiments. To check the applicability of guar gum as a polymer for EOR, polymer solution with different guar gum concentrations was prepared and tested for the viscosity in the different shear rates at room temperature. When the tests showed good results, a polymer solution containing 5000 ppm guar gum was prepared using a laboratory blender. This solution was tumbled for 2 h and allowed to stand overnight to ensure full hydration. The process of tumbling for 2 h and allowed to stand overnight; has been repeated for the preparation of the guar solution in deionized water, brine with different NaCl concentrations, and specific low salinity brine prepared in the laboratory with the description in Table 1.

To minimize oxygen uptake, polymer solutions were stored in closed containers with no other additives for all the experiments. Only one sample was subjected to investigate the optimum quantity of tetrakis hydroxymethyl phosphonium sulfate (THPS) biocide that may control the bacteria degradation on natural polymer.

Dead oil was obtained from an oil field from west Texas. Water and suspended solids were removed by centrifuging the oil for 20 min at 3,000 rpm. The density and viscosity of the dead-crude oil were 0.82 g/cm³ and 3.03 cp, respectively, at ambient conditions.

#### Rheology measurements

The rheological parameters were measured using a high-pressure and high-temperature (HPHT) viscometer (Grace

| Salt         | g/l  |
|--------------|------|
| NaCl         | 0.3  |
| CaCl₂.2H₂O   | 0.01 |
| MgCl₂.6H₂O   | 0.01 |
| KCl          | 0.02 |
| Na₂SO₄       | 0.01 |
| NaHCO₃       | 0.75 |
|              | 1.10 |
M5600). The viscometer used an R1/B5 bob, which required a sample volume of 52 cm$^3$ and had an oil bath for heating; a temperature sensor was present to monitor the sample temperature. A pressure of 400 psi was applied with nitrogen gas to prevent sample boiling. The dynamic viscoelastic properties were measured using a hollow B5 bob in oscillatory testing mode. These tests required sample volumes of 60 cm$^3$.

**Core-flood Setup**

Figure 1 shows a schematic of the core-flood setup utilized in this study. Three stainless-steel piston accumulators were used to store crude oil, brine, and polymer solutions. A positive displacement syringe pump was utilized to inject the polymer solution into the core. The pressure drop across the core was measured by a pressure transducer, and software was used to record the data with time.

Sandstone cores were used (6 in. length and 1.5 in. diameter, bulk volume = 173.6 cm$^3$). Each core plug was first dried in an oven at 150 °F for 24 h. The dried core weight was measured as $W_0$. The core was then saturated with 5 wt% brine (described in Table 1 after an increase of NaCl to 10%) under vacuum for 4 h and then inserted in the core holder; 5 wt% brine was injected at a constant flow rate at room temperature. After stabilization of the pressure drops that across the core, the initial core permeability was determined. The saturated core weight was then weighed as $W_1$. The core pore volume (PV) was calculated from the density of the brine ($\rho_{\text{brine}} = 1.089$ g/cm$^3$ at 77 °F) and the weight difference between the dry and saturated cases (Taylor and Nasr-El-Din 1998) (Eq. 1). The cores were kept in the brine until the time to run the experiment.

$$PV = \frac{W_1 - W_0}{\rho_{\text{brine}}}$$

where PV is the core pore volume, $W_1$ and $W_0$ are the core weight in brine saturated and dry cases, respectively, and $\rho_{\text{brine}}$ is the density of the brine.

After pore volume and permeability measurements were taken, the core was saturated with the crude oil. The core was inserted vertically in the core holder, the backpressure...
was set at 500 psi, and the overburden pressure was set at 1000 psi. The oven temperature was set at 194 ° (90 °C). The crude oil was then injected at 0.2 cm³/min for 5 PV until no water was noted in the core outlet. This step was repeated at 0.5, 1, and 2 cm³/min for 2 PV to ensure reaching the maximum oil saturation in the core. OOIP in the core is equal to the collected displaced water. The weight of the oil-saturated core was measured (W₂). OOIP was also confirmed from the weight difference between the brine saturated and oil-saturated cases (Eq. 2).

\[ V_{oi} = \frac{W_1 - W_2}{\rho_{brine} - \rho_{oil}} \]  

(2)

where \( V_{oi} \) is the OOIP in the core.

The water-flooding stage was followed as a secondary recovery mode. 5 wt% brine was injected at 0.5 cm³/min, and the produced oil was collected for 5 PV until no further oil was recovered from the core. Then, the flow rate was increased to 1 and 2 cm³/min to ensure reaching the residual oil saturation. The weight of the water-flooded core was measured (W₃).

The residual oil volume in the core after the water-flooding stage was calculated by the weight difference between the brine saturated and water-flooded cases (Eq. 3).

\[ V_3 = \frac{W_1 - W_3}{\rho_{brine} - \rho_{oil}} \]  

(3)

where \( V_3 \) is the residual oil volume in the core after the water-flooding stage. \( W_1 \) and \( W_3 \) are the core weights of brine saturated and water-flooded cases, respectively.

The remaining oil was recovered by guar gum polymer which prepared from the same brine with 5000 ppm guar concentration. 2.5 PV (87 cm³) brine followed by 0.5 PV (17.5 cm³) guar gum and 1.5 PV (52 cm³) brine were flooded in a constant flow rate.

Results and discussion

Effect of shear rate and concentration on viscosity measurements

The viscosity was measured in different shear rates (Fig. 2). Guar polymer solutions show pseudoplastic or shear-thinning performance, where viscosity decreasing with increasing shear rate is very clear as noticed by many other high molecular weight polymers (Mudgil et al. 2014). The viscosity reduction is due to uncoiling and alignment of guar polymer chains when exposed to shear flow (Khan et al. 2009; Samanta 2011). Grace M 5600 was run for the same sample with different shear rates to check the value of the approximate viscosity for guar gum polymer. The results show the average viscosity for the 5000 ppm guar polymer in deionized water at 77 °F is approximately 500, 300, and 150 cp for shear rate 10, 30, and 100 S⁻¹, respectively (Fig. 3).

5000, 4000, 3000, and 2000 ppm guar concentration were tested to show the effect of concentration of guar gum versus

![Fig. 3 Viscosity of 5000 ppm guar gum polymer at a different shear rate](image-url)

![Fig. 4 The relationship between the viscosity of the polymer solution and polymer concentration](image-url)

![Fig. 2 Variation of 5000 ppm guar gum polymer viscosity with the shear rate at 77°F](image-url)
different shear rate. The results showed very low viscosity (2–3 cp) at a temperature above 210 °F at 100 S$^{-1}$ shear rates for concentration less than 5000 ppm. The relationship between the viscosity of the guar gum polymer and the guar concentration is presented in Fig. 4. Although the viscosity measurements were done in 210 °F, it is clear that from the plot, the polymer has good viscosity increasing performance, and the viscosity of the polymer is directly proportional to the increase in polymer concentration which agreed with many authors (Nasr-El-Din et al. 1991; Samanta 2011; Purwono et al. 2012).

Effect of salinity and temperature

The types and amounts of salts present in brine solutions and the temperature at ambient conditions were significantly affecting the polymer rheology. Therefore, complete knowledge of polymer behavior and rheology is very important for polymer flooding (Khan et al. 2009). Many studies proved that HPAM properties affected by salinity and temperature above 70 °C (Abidin et al. 2012). Gao (2013) found that 10 cp viscosity can be achieved for HPAM polymer at 90 °C (194 °F) when 3000 ppm concentration was used (Fig. 5).

In the experiments of this study, a constant shear rate as 7.34 S$^{-1}$ was used to test the effect of temperature on 5000 ppm guar gum polymer (Fig. 6). It can be noticed that polymer viscosity diminished at a higher temperature just like other known polymers. As the temperature increases, the average speed of the molecules in the liquid increases and the time they spent in contact with their nearest molecules decreases (Khan et al. 2009). As a result, the average intermolecular forces decrease. The results showed good stability of guar gum polymer even at high temperature where more than 100 cp viscosity can be achieved at 210 °F at 7.34 S$^{-1}$ shear rate for polymer prepared in deionized water (Fig. 6). This result is better than xanthan gum which has significant hydrolytic degradation above 70 °C (158 °F) (Abidin et al. 2012) and also is better than HPAM if it compared to Fig. 5. From Fig. 6, guar polymer shows good viscosity even in the presence of 20% NaCl where the viscosity is acceptable for temperature less than 190 °F. After this temperature, a great reduction of viscosity has noticed. When the polymer chain stretched in distilled water due to the force of repulsion between the negative charges in the salt chain, there will be a reduction in the polymer viscosity (Fig. 6) (Abidin et al. 2012; Samanta et al. 2012).

Figure 7 compares the polymer viscosity versus the different shear rate at 77 °F and 210 °F. The results showed equal viscosity at low shear rate; however, a noticed difference is clear in 100 S$^{-1}$ shear rates and above.
Viscosity for brine described in Table 1 was measured at 77º F and compared with the polymer in deionized water (Fig. 8). There is no difference for the polymers viscosity that is because the brine has very low salt concentration. From the results, it can be safe to use the guar gum polymer for reservoirs with low-salinity even at high temperature, where Fig. 9 shows the viscosity reduction in 210º F for the polymer in low salinity brine; however, more than 50 cp viscosity can be achieved for 5000 ppm guar concentration for a shear rate less than 100 S⁻¹.

Figure 10 shows the effect of temperature on guar gum polymer viscosity for a polymer solution prepared with 2% NaCl and 5000 ppm guar. The polymer has an acceptable viscosity for temperature less than 210º F. Experiments also showed promising results for 5000 ppm guar polymer prepared with 10% and 20% NaCl; however, more experiments are needed to confirm the values of polymer viscosity.

Bio degradation

The polymer is utilized to increase the viscosity of the mobile aqueous phase. The efficacy and success of the polymer immersion process can be measured by the polymer’s ability to maintain viscosity while spreading in the reservoir (Silva et al. 2018). Polymers, in particular, natural-polymers are susceptible to microbial degradation. 5000 ppm guar was used in deionized water and viscosity was measured in different shear rates after 24 h of preparation, 7 days, and 15 days and stored at room temperature in closed containers. The results show that the viscosity was gradually...
decreased and completely lost after 15 days at a high shear rate (Figs. 11 and 12). This study confirmed that it is very important to monitor the guar gum polymer quality in the oil field by injecting suitable biocide to prevent microbial degradation.

To find the suitable and optimum biocide for guar gum polymer, 25 ppm of tetrakis hydroxymethyl phosphonium sulfate (THPS) biocide was added to the polymer solution in deionized water and allowed to stand overnight. On the next day; the solution was separated into two phases with a large viscosity reduction, whereas per Kesavan et al. (2014): "fluids contain a polysaccharide- mainly guar or guar derivatives- would be desirable to use THPS as a biocide and still maintain the viscosity of the fluid". For future works; we recommended to test glutaraldehyde as a biocide for guar polymer.

**Flooding experiments results**

Water flooding followed by polymer flooding was implemented using the system in Fig. 1. The results are shown in Table 2. Figure 12 shows the cumulative oil production during the water and polymer flooding stages. At initial steady-state conditions where the only oil was producing, the produced oil volume equaled the injected water volume. Water breakthrough occurred after around 0.3 PV injected water where the recovery factor was 70%. With continuous injection up to 8 PV, the recovery factor increased 4–74%.

Polymer flooding was then able to increase the sweep efficiency and reduces the viscous fingering. Hence, the oil recovery factor increased by 16%. Although, many researchers observed that; water flood as general still leaves 50–70% oil in the formation (Abidin et al. 2012), in this experiment; 74% of the total oil in place has been produced using water flooding. That is because high permeability core (1.2 Darcy) and light oil have been used. After guar gum polymer flooding, an additional 16% of the original oil in place has been produced (3.45 ml) which is about 60% of the oil remaining after water flooding (Fig. 13). From this study, guar gum can be recommended as a polymer even during the secondary recovery stage.

**Conclusion and recommendations**

Guar gum polymer has been tested for its possibility to be used as an EOR chemical. The results show that guar gum has potential as EOR environmentally friendly polymer even at reservoir temperature up to 210º F and reservoirs with water salinity up to 20% NaCl. The outcomes of this study can be summarized that guar gum represents good stability and rheological properties in high temperature and salinity. However, Guar is just like other natural polymers and is susceptible to microbial degradation. As a result of this study;

| Property                        | Value   |
|---------------------------------|---------|
| 1 Total pore volume, ml         | 34.9    |
| 2 Permeability, md              | 1200    |
| 3 $S_{wc}$                      | 38      |
| 4 Total oil in place, ml        | 21.6    |
| 5 Total oil produced by water flooding, ml | 16 (74%) |
| 6 Total oil produced by polymer flooding, ml | 3.45 (16%) |

Fig. 13 Water and guar gum polymer flooding
tetakis hydroxymethyl phosphonium sulfate (THPS) is not recommended as a biocide with guar gum. Also, the flooding experiment shows that the recovery factor can be increased by 16% when guar polymer is used.

**Acknowledgments** The authors would like to acknowledge the sponsorship of the first author by Texas A&M Engineering Experiment Station Gas & Fuels Research Center research internship at Texas A&M University to conduct the experimental part of this study at the Harold Vance Department of Petroleum Engineering. Thanks are also extended to steering and technical committees of “Guar and Arabic Gums Properties Improvement for Potential Use in EOR & Sand Control in Sudanese Oil Fields” project, 2015, for their general support.

**Funding** There is no funding provided to this study.

**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

**References**

Abidin AZ, Puspasari T, Nugroho WA (2012) Polymers for Enhanced Oil Recovery Technology. Procedia Chem 4:11–16. https://doi.org/10.1016/j.proche.2012.06.002

Airey GD (2003) Rheological properties of styrene butadiene styrene polymer modified road bitumens [U+2606]. Fuel 82(14):1709–1719. https://doi.org/10.1016/S0016-2361(03)00146-7

Almansour AO, AlQuraishi AA, AlHussainan SN, AlYami HQ (2017) Efficiency of enhanced oil recovery using polymer-augmented salt salinity flooding. J Pet Explor Prod Technol 7(4):1149–1158. https://doi.org/10.1007/s13202-017-0333-5

Clarke A, Howe AM, Mitchell J, Staniland J, Hawkes LA (2016) How viscoelastic-polymer flooding enhances displacement efficiency. SPE J 21(3):675–687. https://doi.org/10.2118/174654-MS

Gao C (2013) Viscosity of partially hydrolyzed polyacrylamide under shearing and heat. J Pet Explor Prod Technol 2013(3):203–206. https://doi.org/10.1007/s13202-013-0051-4

Gao S, Li H, Li H (1995) Laboratory investigation of combination of alkaline surfactant-polymer for daqing EOR. SPE 27631-PA. SPE Reserv Eng 10(03):194–197. https://doi.org/10.2118/27631-PA

Hassan A, Bruining H, Musa T, Chahardowi M (2017) The use of RFID technology to measure the compositions of diethyl ether–oil–brine mixtures in enhanced imbibition experiments. J Pet Sci Eng 156:769–779. https://doi.org/10.1016/j.petrol.2017.06.051

Hassan AM, Ayoub M, Eissa M, Musa T, Bruining H, Farajzadeh R (2019a) Exergy return on exergy investment analysis of natural-polymer (guar-Arabic gum) enhanced oil recovery process. Energy 181:162–172. https://doi.org/10.1016/j.energy.2019.05.137

Hassan A, Ayoub M, Eissa M, Musa T, Bruining H, Zitha P (2019b) Development of an integrated RFID-IC technology for on-line viscosity measurements in enhanced oil recovery processes. J Pet Explor Prod Technol 9:2605–2612. https://doi.org/10.1007/s13202-019-0638-5

Hou J, Liu Z, Zhang S, Yang J (2005) The role of viscoelasticity of alkali/surfactant/polymer solutions in enhanced oil recovery. J Pet Sci Eng 47(3–4):219–235. https://doi.org/10.1016/j.petrol.12005.04.001

Huggins ML (1942) The viscosity of dilute solutions of long-chain molecules. I. Dependence on concentration. J Am Chem Soc 64(11):2716–2718. https://doi.org/10.1021/ja01263a056

Hymowitz WA (1979) Guar: production, nutrition and industrial use. Purdue University Press, Lafayette, Indiana

Ibrahim AF, Emrani A, Nasraldin H (2017). Stabilized CO2 Foam for EOR Applications, CMTC-486215-MS, Carbon Management Technology Conference. Houston, Texas, USA, 17–20. https://doi.org/10.7122/486215-MS

Jang HY, Zhang Ke, Chon BH, Choi HI (2015) Enhanced oil recovery performance and viscosity characteristics of polysaccharide xanthan gum solution. J Ind Eng Chem 21(741–745):2015. https://doi.org/10.1016/j.jiec.2014.04.005

Kesavan S, Woodward G, Adeleji A, Curtis T, Smith F (2014) Methods for controlling depolymerization of polymer compositions, US Patent 8, 828, 914.

Khan MY, Samanta A, Ojha K, Mandal A (2009) Design of alkaline/surfactant/polymer (ASP) slug and its use in enhanced oil recovery. Pet Sci Technol 27(17):1926–1942. https://doi.org/10.1080/1946460802662765

Kim DH, Lee S, Ahn CH, Huh C, Park GA (2010) Development of a viscoelastic property database for EOR polymers. Society of Petroleum Engineers, In SPE Improved Oil Recovery Symposium. https://doi.org/10.2118/129971-MS

Lee KS, Lee JH (2019) Hybrid enhanced oil recovery using smart waterflooding. Gulf Professional Publishing.

Ministry of Oil and Gas (2015) Guar and Arabic gums properties improvement for potential use in EOR & sand control in Sudanese oil fields project, first report (PR00030R1). Ministry of oil and gas, Sudan

Mohammadi H, Jerauld G (2012) Mechanistic modeling of the benefit of combining polymer with low salinity water for enhanced oil recovery. In: SPE Improved Oil Recovery Symposium. Society of Petroleum Engineers https://doi.org/10.2118/153161-MS

Mudgil D, Barak S, Khatkar BS (2014) Guar gum: processing, properties and food applications—a review. J Food Sci Technol 51:409–418. https://doi.org/10.1007/s13202-013-0051-4

Nasr-El-Din HA, Noy JL (1992) Flow behavior of alkali, surfactant, and xanthan solutions used for enhanced oil recovery. J Revue de l’Institut Francais du Petrole 4(6):771–791

Nasr-El-Din HA, Hawkins BF, Green KA (1991) Viscosity behavior of alkaline, surfactant, polyacrylamide solutions used for enhanced oil recovery. Society of petroleum engineers, SPE International Symposium on Oilfield Chemistry, 20–22 February, Anaheim, California https://doi.org/10.2118/21028-MS

Ojlajre AA (2014) Review of ASP EOR (alkaline surfactant polymer enhanced oil recovery) technology in the petroleum industry Prospects and challenges. Energy 77:963–982

Purwono S, Murachman R, Rochmadi, Hasokowati W, Irawan D, Munir MA, Endriadi Y (2012) Polymer flooding for improving oil recovery, Proceeding 19th Regional Symposium of Chemical Engineering.

Samanta A, Ojha K, Mandal A (2011) The characterization of natural surfactant and polymer and their use in enhanced recovery of oil. Pet Sci Technol 29(7):765–777

Samanta A, Bera A, Ojha K, Mandal A (2012) Comparative studies on enhanced oil recovery by alkali–surfactant and polymer flooding. J Petrol Explor Prod Technol 2:67–74. https://doi.org/10.1007/s13202-012-0021-2
Enhanced oil recovery (EOR) by combined low salinity water/polymer flooding. Energy Fuels 27(3):1223–1235. https://doi.org/10.1021/ef301538e

Modern chemical enhanced oil recovery: theory and practice. Gulf Professional Publishing.

Alkaline-polymer flooding: enhanced oil recovery field case studies, pages 169–178. Elsevier, 2013.

Status of polymer-flooding technology. J Can Pet Technol 54(02):116–126. https://doi.org/10.2118/174541-PA

A polymer flooding mechanism for mature oil fields: Laboratory measurements and field results interpretation. J Pet Sci Eng 161(2018):468–475. https://doi.org/10.1016/j.petrol.2017.12.008

Polymer-improved oil recovery, 115 glasgow. Scotland: Blackie & Son, pages 126–163

Viability of biopolymers for enhanced oil recovery. J Dispersion Sci Technol 37(8):1160–1169. https://doi.org/10.1080/01932691.2015.1088450

Water-soluble hydrophobically associating polymers for improved oil recovery: a literature review. J Pet Sci Eng 19(3–4):265–280. https://doi.org/10.1016/S0920-4105(97)00048-X

Evaluation of polymer properties for potential selection in enhanced oil recovery. Chem Eng Trans 65(343–348):2018. https://doi.org/10.3303/CET186S058

Application of a novel polymer system in chemical enhanced oil recovery (EOR). Colloid Poly Sci 281(11):1046–1054. https://doi.org/10.1007/s00396-003-0873-6

Smart water synergy with surfactant polymer flooding for efficient oil mobilization in carbonates. In SPE EOR Conference at Oil and Gas West Asia. Society of Petroleum Engineers https://doi.org/10.2118/190334-MS

Interactions between alkali/surfactant/polymer and their effects on emulsion stability. Colloids Surf A Physicochem Eng Asp 175(1–2):243–247. https://doi.org/10.1016/S0927-7757(00)00461-1

Sensitivity analysis of hydraulic fracture geometry in shale gas reservoirs. J Pet Sci Eng 113(1–7):2014. https://doi.org/10.1016/j.petrol.2013.12.005

Polymer flooding, volume 24. Elsevier.

Guar: agronomy, production, industrial use, and nutrition. Purdue University Press. https://doi.org/10.2307/2806779

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.