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Synergistic Effects of ZnO Nanoparticles and Environmental Factors on Biopolymer Solutions for Oil Recovery via Core Flooding

Mohammed Khairy M.Salih [1], Sherwan M.Simo[1,2] , Abbas khaksar Manshad [3]

[1] Department of Petroleum Engineering, University of Zakho, Zakho 42002, Kurdistan Region, Iraq.
[2] Engineering Research Center, University of Zakho, Zakho 42002, Kurdistan Region, Iraq.
[3] Department of Petroleum Engineering, Abadan Faculty of Petroleum Engineering, Petroleum University of Technology 63187-14317, Abadan, Iran.
Email: mohammed.sailh@uoz.edu.krd , Sherwan.simo@uoz.edu.krd , akmanshad113@gmail.com

Abstract

This study investigates the rheological impact of salt content and zinc oxide (ZnO) nanoparticles on guar gum and xanthan gum biopolymer solutions, both individually and in blends, for potential application in enhanced oil recovery (EOR). A series of shear viscosity measurements were conducted over a wide range of shear rates, temperatures, and polymer concentrations (400–2400 ppm) to evaluate how these additives influence fluid behavior under reservoir-like conditions.The results demonstrate that guar gum viscosity increases with salinity at both low and high polymer concentrations. In contrast, xanthan gum solutions exhibit high sensitivity to salt, resulting in a significant reduction in shear viscosity. Evaluation of xanthan/guar mixtures at ratios of 1:1, 1:2, and 2:1 revealed no noticeable synergistic effect. Furthermore, although salinity strongly influenced the rheological behavior of most biopolymer–ZnO systems, formulations containing a higher proportion of guar gum remained relatively stable.The findings suggest that a combination of xanthan and guar solutions integrated with 0.3 wt% ZnO nanoparticles provides a promising strategy for controlling fluid morphology and rheological properties in EOR applications. In addition, at 2400 ppm xanthan concentration, the resistance factor (RF) and residual resistance factor (RRF) exhibited very high values of 1504.08 and 784.8, respectively. Conversely, at 1200 ppm guar gum concentration, the RF and RRF values were significantly lower, at 23.64 and 19.08, respectively.

Keywords: Xanthan , Rheology , Guar gum, salt , core flooding , temperature , viscosity , shear rate , Zinc oxide nanoparticle.

1 Introduction

Xanthan gum and guar gum are natural polysaccharides that are widely used in the food industry due to their excellent thickening, stabilizing, and texture-modifying properties. Even at relatively low concentrations, both polymers exhibit high viscosity in aqueous solutions, making them attractive for various industrial applications. Beyond food processing, these biopolymers have received increasing attention in non-food sectors, particularly in enhanced oil recovery (EOR), where viscosity control of injected fluids is essential for improving sweep efficiency and mobility ratio. One of the most distinctive rheological characteristics of biopolymers is their ability to exhibit synergistic behavior when blended. This synergistic effect refers to a situation in which the viscosity of a polymer mixture exceeds that of the individual components at the same total concentration. Such behavior has been extensively reported for xanthan/guar systems and has attracted significant interest for EOR applications, where higher viscosity at lower polymer dosage is economically and operationally advantageous. Comprehensive discussions of the molecular structure, chemical reactions, and physicochemical properties of xanthan and guar can be found in the literature [1, 2].

Xanthan gum generally exhibits higher viscosity than guar gum due to its higher molecular weight and rigid molecular conformation. Xanthan possesses a stabilized, helical, ordered structure, partly caused by acetyl groups attached to its backbone, which restrict chain flexibility. As a result, de-acetylated xanthan is often preferred in polymer blends to enhance synergistic interactions with guar. Several studies have reported that xanthan/guar mixtures can display cooperative behavior, leading to viscosities significantly higher than those of neat gums [3-5]. The rheological behavior of polysaccharide solutions is strongly influenced by salinity. In aqueous solutions of anionic or cationic polysaccharides, the addition of salt induces a polyelectrolyte effect, in which electrostatic charges along the polymer chains are shielded by ions. This shielding weakens intermolecular repulsion and can reduce chain expansion, leading

to a decrease in solution viscosity [6] . Conversely, under certain conditions, disruption of electrostatic shielding may allow polymer chains to extend and interact more effectively, resulting in increased viscosity [7] . Despite the importance of salinity, the number of studies addressing the effect of salt on the rheology of xanthan/guar mixtures remains relatively limited [4]. Previous investigations have shown that salinity can significantly suppress synergistic effects in xanthan/guar systems. For example, the addition of up to 2 wt.% potassium salt to a guar/xanthan mixture at a 4:1 ratio resulted in a substantial reduction in viscosity [4] . Other studies reported strong synergism at xanthan/guar ratios of 60/40 and 80/20 in fresh water and weakly acidic conditions; however, this synergism disappeared at high salinity levels (e.g., 40 mM NaCl), where overall viscosities were markedly lower [8]. These findings indicate that salt not only reduces the viscosity of xanthan/guar mixtures but also strongly influences their cooperative behavior. In recent years, zinc oxide (ZnO) nanoparticles have attracted growing interest for chemical EOR applications[9], and several studies have demonstrated their potential to improve fluid performance [10] . ZnO nanoparticles are particularly appealing due to their low toxicity, biocompatibility, diverse morphologies, and favorable physicochemical stability [11]. Additional advantageous properties include low synthesis temperature, strong adsorption capacity, high catalytic activity, and excellent chemical durability, making ZnO nanoparticles suitable for harsh reservoir environments[12]. When transported through porous media, nanoparticles may interact with pore throats or rock surfaces, increasing flow resistance and modifying fluid mobility[13] . Moreover, ZnO nanoparticles possess surface hydroxyl (–OH) groups, which can form hydrogen bonds with the hydroxyl and carboxyl functional groups present in xanthan and guar polymers, potentially altering solution rheology. Despite extensive research on polymer flooding and nanoparticle-assisted EOR, the combined effects of salinity, divalent ions, and ZnO nanoparticles on the rheology of xanthan/guar mixtures remain insufficiently understood, particularly under reservoir-relevant conditions. Most existing studies focus on either polymer blending or nanoparticle addition independently, with limited attention given to mixed polymer–nanoparticle systems in high-salinity environments.

The novelty of the present work lies in systematically investigating the coupled effects of sodium chloride and calcium chloride salinity, temperature, and ZnO nanoparticle concentration on the steady-state flow behavior of xanthan/guar mixtures. The main objective is to evaluate how salinity and nanoparticles influence viscosity, synergism, and flow characteristics of these biopolymer systems. This study is particularly relevant to enhanced oil recovery in Saudi reservoirs, which are characterized by high salinity and complex ionic compositions. The results are expected to provide valuable insights for designing robust polymer–nanoparticle formulations capable of maintaining favorable rheological properties under harsh reservoir conditions.

2 Research projects

2. 1 Materials utilized

The experimental framework utilized two distinct material sources: synthesized guar gum nanoparticles and existing commercial-grade biopolymers. Specifically, xanthan ,Salts and ZnO nanoparticles were employed as existing commercial .

2. 1. 1 Synthesis the guar gum powder from seed of guar

Processing methods for guar gum vary among processing plants. The primary flowchart for the guar gum manufacturing process is shown in Fig. 1. When guar seeds are removed from their pods, they are spherical, dark in color, and smaller than pea seeds.

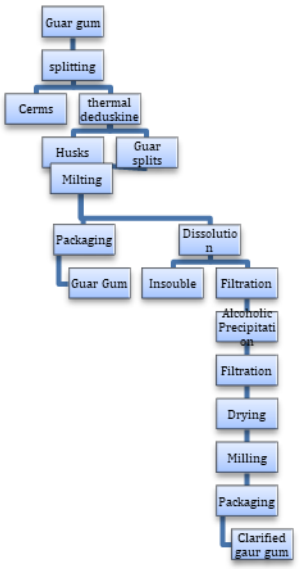


Figure 1: Industrial guar gum manufacturing flow diagram.

Industrial extraction of guar gum from the seeds is essentially a physical process involving differential attrition, roasting, sifting, and polishing. After the seeds are broken, the germ and endosperm are separated. Each seed yields two endosperm halves, known as un-husked guar splits. These endosperm halves are further polished to remove the thin fibrous outer layer, producing refined guar splits.The hull (husk) and germ portions of the guar seeds, collectively referred to as guar meal, are major byproducts of guar gum powder production and are commonly used as cattle feed. Depending on the desired final product, various processing and finishing techniques are applied to convert refined guar splits into powders, commonly known as guar gum. The refined splits are first pre-hydrated and crushed in a flaker mill, then uniformly conveyed to an ultra-fine grinder, where they are ground with minimal heat generation. After grinding, the material is dried and passed through a series of screens to classify it according to particle size. Different grades of guar gum are produced based on moisture loss rate, color, screen size, and viscosity potential.

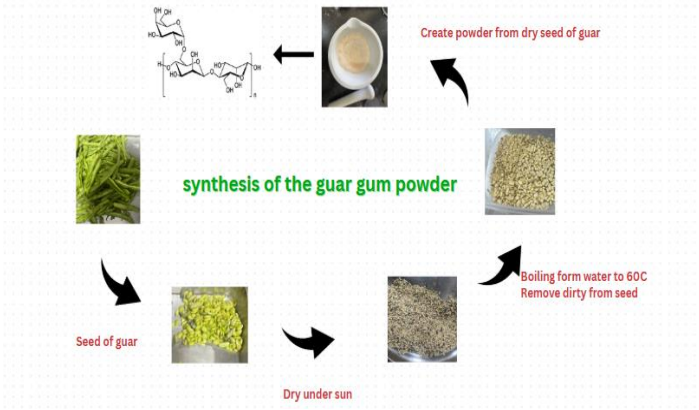


Figure 2: Prepare of guar powder from seed of guar.

2. 1. 2 Xanthan powder

Xanthan gum used in this study was supplied by Sigma-Aldrich Co. and commercially procured through Sobar Company in Sulaymaniyah, Iraq, ensuring consistent quality and suitability for all experimental rheological and thermal analyses conducted.

Figure 3 : Xanthan powder

2. 1. 3 Salts

Brine solutions were prepared using analytical-grade calcium chloride ($CaCl_2$) and sodium chloride (NaCl), which were dissolved in deionized water at the required concentrations to simulate saline conditions during the experimental investigations.

2. 1. 4 Zinc Oxide nanoparticle

Zinc oxide nanoparticles used in this study were supplied by Sigma-Aldrich Co. and procured through Sobar Company Sulaymaniyah, Iraq.

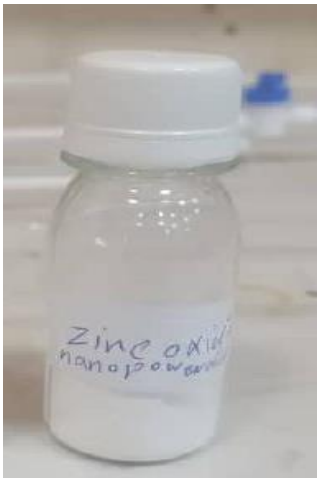


Figure 4: Zinc oxide nanoparticle (nano-material)

2. 2 Preparing the sample

Water-based solutions of guar gum, xanthan gum, and their mixtures were prepared using purified water at polymer concentrations ranging from 400 to 2400 ppm, with incremental increases of 400 ppm. Brine samples were prepared by dissolving calcium chloride and sodium chloride at a total salinity of 15% (w/v), using an 70/30 weight ratio of $CaCl_2$ to NaCl. Xanthan-to-guar blend ratios of 1:1, 1:2, and 2:1 were investigated. Zinc oxide nanoparticles were subsequently added to the polymer and polymer-blend solutions at concentrations of(0.10, 0.15, 0.20, 0.25, and 0.30) wt%.

Figure 5: Some samples of xanthan /guar solution at temperature room

2. 3 Examinations of rheology

The prepared samples were subjected to rheological testing using a type AR-G2 rotational rheometer, which TA manufactured., Instrument. For all samples, a concentrated cylinder was employed to carry out steady state multiple shear using a conical din rotor that was 28 mm in diameter and 42 mm in height ln order to determine the relationship between shear viscosity and shear rate at various temperatures, starting at 20°C and rising by 20°C to 80°C.

Figure 6: Rotational rheometer of type AR-G2

2. 4 Experiments of displacement

Firsty, investigate The efficiency of solutions made of polymers in preventing extreme water formation, single- phase displacement experiments were performed using sandstone core samples that were characterized by uniform petrophysical characteristics and consistent distribution of pore sizes , the core samples had cylindrical cores that were 3 inches length and 1.5 inches in diameter, with extremely close porosity and permeability. To perform displacement runs, Utilizing a Core Flooding Unit Model CFS 830. Initially, A dry core sample was first put in a desiccator and vacuumed until the core sample was saturated. The sample became saturated with the brine solution after the proper vacuum pressure was achieved. the sample of core is porosity using the saturating fluid density was calculated using both the sample's weight when saturated and the weight of core is dry. After the core sample was completely saturated, it was put in the core holder and put under 2100 psi of confining pressure. The oven was preheated to 70°C, the back pressure regulator was set to atmospheric pressure. Brine was introduced at various flow rates once The temperature had been attained across the unit, and the pressure decrease was noted once it had stabilized. To find the sample liquid permeability, Darcy's law was applied. Following that, The core sample received a gradual injection of polymer solution at a rate of 1 cm^3/min. an equal to 18 s^{-1} for shear rate, and the growing pressure decrease over the core sample was continuously monitored. The infusion went on until the stable steady pressure drop indicated that full absorption had been reached. Following that, a pump was turned on to let Before the flow was routed to the brine accumulator, the brine solution passed through the sample rock and flushed the non-adsorbed polymer. Reduction in pressure at this point commenced to decrease, and the experiment was terminated when the pressure drop steadied. After The sample was then taken out of the core holder and allowed to air dry at the standard temperature.

2. 4. 1 The experimental configuration

As “Figure 7,” Shows a schematic representation of the core flooding unit. A syringe pump, three transfer vessels, a core holder, a hand pump, and a pressure transducer that reports pressure readings to a computer are the main parts of the apparatus. To seal the space around the sand pack and stop leaks from it, a rubber sleeve is placed within the core holder and operated by hand pump. Sand particles are progressively placed within the rubber sleeve and evenly packed under continuous pressure to guarantee uniform porosity throughout the sand pack.

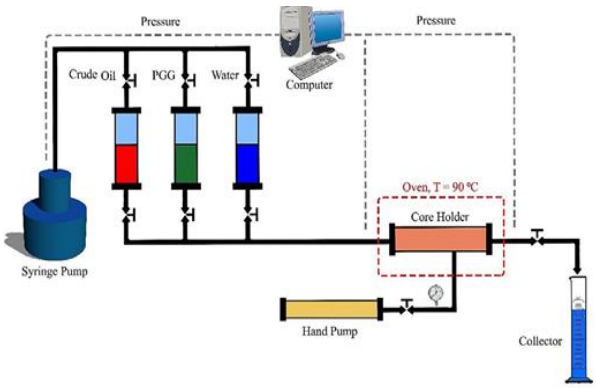


Figure 7: Shows the core flooding unit schematically.

3 Discussions and outcomes

Shear viscosity as a function of rate of shear for biopolymer non-brine solutions at varying polymer concentrations and temperatures. is displayed in “Figure 8 and 9,”. like expected, xanthan solutions have higher viscosity values than guar solutions do; yet, guar acts like a Newtonian substance at comparatively lower levels of concentrations (i.e., 800 ppm), as show in “Figure 8,”. “Figures 10 and 11,” illustrate how the concentration of brine affects the shear viscosity of biopolymer mixtures . Like illustrated at the “Figure 10,” it is evident that higher brine concentrations up to 30 % have a tendency to noticeably raise guar viscosity. On the other hand, “Figure 11,” illustrates how brine is observed to significantly lower viscosity in xanthan solutions. Therefore, it is possible to draw the conclusion The ionic shielding effect of brine is associated with xanthan solutions.

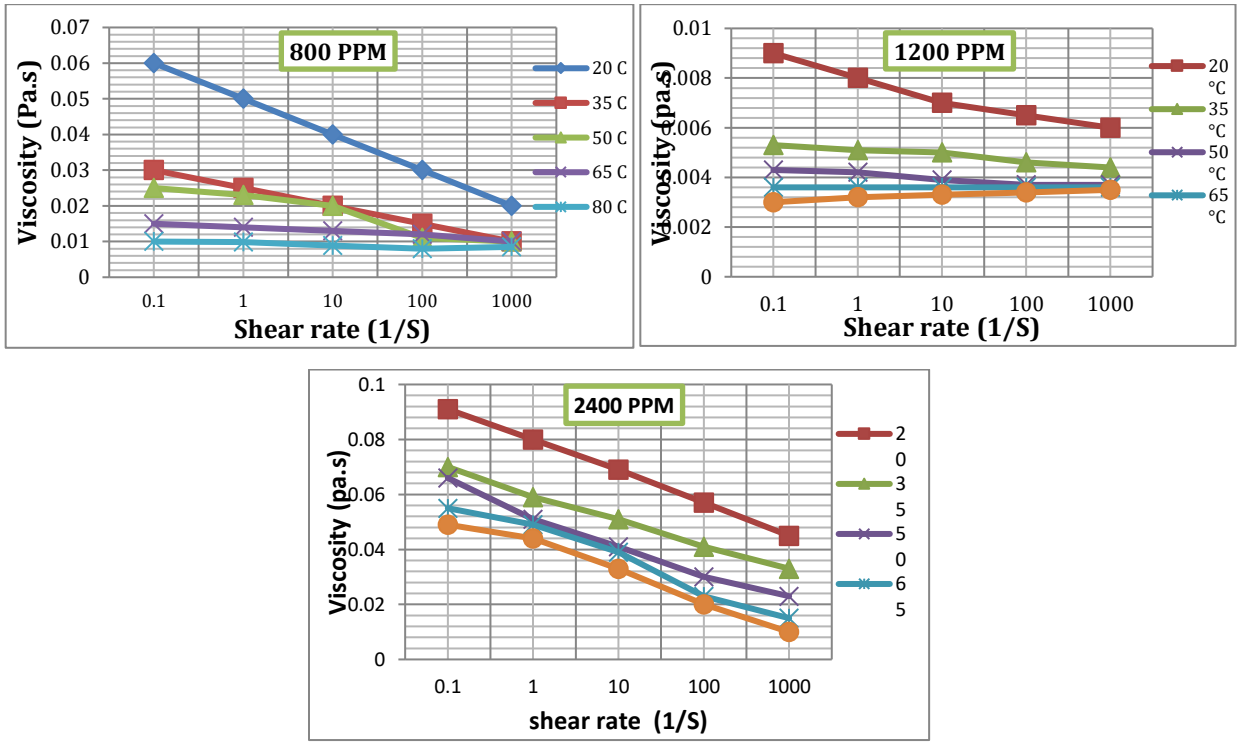


Figure 8: Profile of shear flow for guar solutions containing non-brine at concentrations of (800 ,1200,2400) PPM

In the “Figure 8,“ the study of shear flow profiles for guar gum solutions at varying concentrations (800, 1200, and 2400 ppm) in non-brine water demonstrates a clear **concentration-dependent rheological behavior**, Guar gum exhibits shear-thinning behavior across all tested concentrations viscosity decreases with raising shear rate.increasing levels leadsto higher initial (zero-shear) viscosity, due to greater molecular entanglement and stronger intermolecular interactions among guar chains.the degree of shear-thinning becomes more pronounced at higher concentrations. this is because more entangled structures are broken down under shear, resulting in a sharper drop in viscosity.at 800 ppm, the solution behaves closer to Newtonian, with lower viscosity and mild shear-thinning.at 1200 and 2400 ppm, the guar solutions exhibit significantly higher viscosities and stronger non-Newtonian behavior, making them more suitable for applications requiring viscosity control under flow , the rheological performance of guar gum solutions can be effectively tailored by adjusting the concentration, making it a versatile thickener in shear-sensitive environments.as “Table 1,” presents the effect of xanthan concentration on the xanthan profile without brine. The results shown in “Figure 8,” indicate that the viscosity of guar gum solutions without brine at 20 °C increases with polymer concentration. At 800 ppm, the viscosity ranges from 0.02 to 0.06 Pa·s across different shear rates. For the 1200 ppm solution at 20 °C, the viscosity varies from 0.006 to 0.0096 Pa·s. In contrast, at 2400 ppm, the viscosity is significantly higher, increasing from 0.043 to 0.09 Pa·s over the investigated shear rate range.

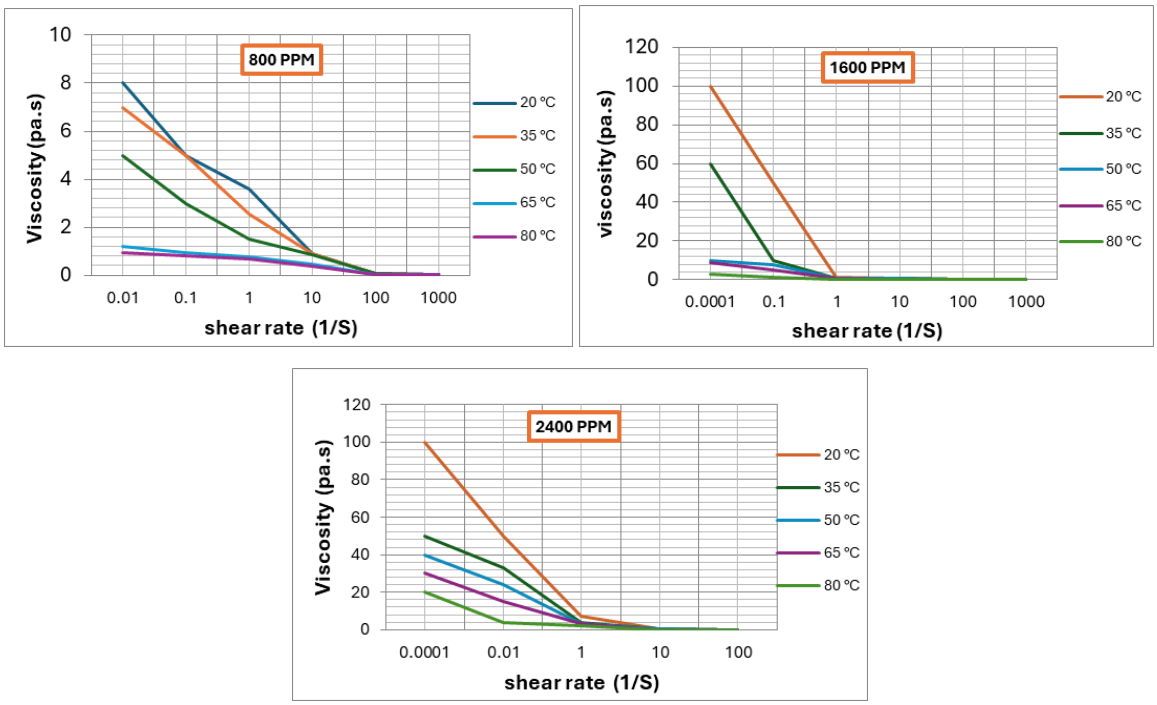


Figure 9: Illustrates the shear flow profile for solutions of non-brine xanthan at varying concentrations.

The results shown in "Figure 9," indicate that the viscosity of xanthan solutions without brine at 20 °C increases with polymer concentration. At 800 ppm, the viscosity ranges from 0.02 to 8 Pa•s across different shear rates. For the 1200 ppm solution at 20 °C, the viscosity varies from 0.1 to 100 Pa•s. In contrast, at 2400 ppm, the viscosity is significantly higher, increasing from 0.043 to 101 Pa•s over the investigated shear rate range.

Table 1 : Explain of the profile of non-brine & xanthan solution.

Concentration	Temp (°C)	Viscosity Trend	Shear-Thinning	Explanation
800 ppm	20	Low	Mild	Weak entanglement, low T
	80	Very low	Weak	Thermal thinning dominates
1200 ppm	20	Medium	Strong	Moderate entanglement
	80	Noticeable drop	Reduced	Some structure loss
2400 ppm	20	Very high	Very strong	Dense network
	80	Moderate	Reduced	Heat disrupts structure

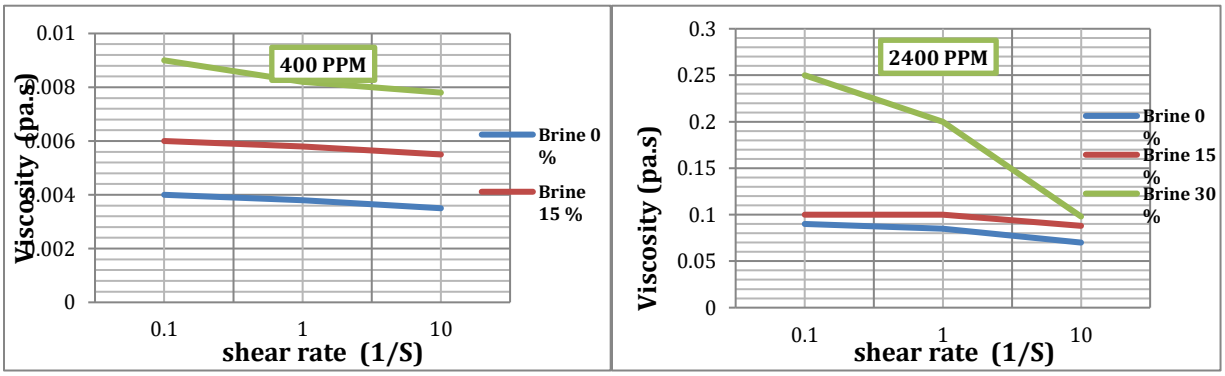


Figure 10: Illustrates Brine's effect on the rheological characteristics of guar solutions at two guar concentrations (T = 20°C).

The results shown in "Figure 10," indicate that the viscosity of guar gum solutions 30 % brine at 20 °C increases with brine concentration. At 400 ppm, the viscosity ranges from 0.0074 to 0.0090 Pa•s across different shear rates,at

2400 ppm, the viscosity is significantly higher, increasing from 0.0101 to 0.25 Pa•s over the investigated shear rate range. in the 15% brine at 20 °C increases with brine concentration. At 400 ppm, the viscosity ranges from 0.0055 to 0.006 Pa•s across different shear rates,at 2400 ppm, the viscosity is significantly higher, increasing from 0.090 to 0.1 Pa•s over the investigated shear rate range.

The rheological properties of guar solutions at 20 °C are strongly influenced by brine concentration. Low brine concentrations may initially cause a slight increase in viscosity due to reduced electrostatic repulsion, which promotes improved polymer chain interactions. However, moderate to high brine concentrations (≥3–5%) lead to a reduction in viscosity and a weakening of shear-thinning behavior, particularly in dilute guar solutions (800 ppm). In contrast, concentrated guar solutions (2400 ppm) exhibit greater resistance to salinity effects because of stronger polymer chain entanglement and a more developed gel structure, although a gradual decrease in viscosity is still observed as brine concentration increases.

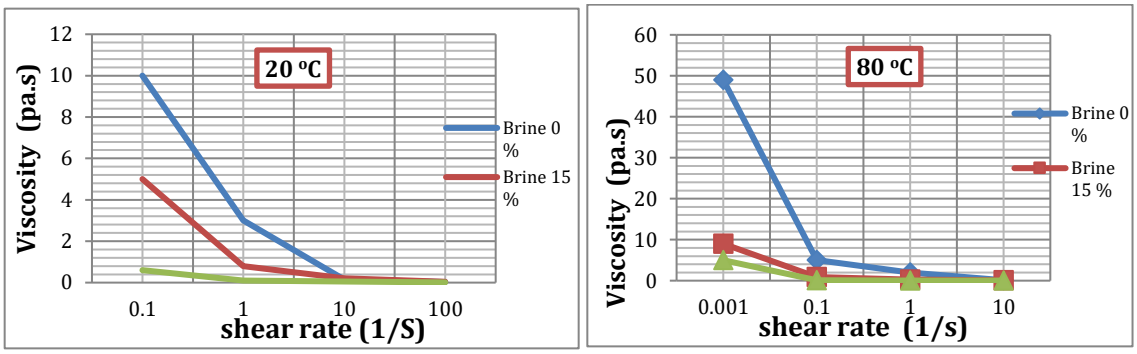


Figure 11: Illustrates the impact of brine concentrations on the xanthan solution's rheological characteristics at a 2400 ppm concentration, recorded between 20°C and 80°C.

The results shown in "Figure 11," indicate that the viscosity of xanthan solutions 0% brine decreases with brine concentration. At 2400 ppm, the viscosity ranges from 0.01 to 10 Pa•s across different shear rates,at 2400 ppm with 80 °C the viscosity is significantly higher, increasing from 0.0101 to 50 Pa•s over the investigated shear rate range. In the 15 % brine at 2400 ppm decrease with brine concentration. At 20 ºC, the viscosity ranges from 0.0055 to 5 Pa•s across different shear rates,at 2400 ppm, the viscosity is significantly higher, increasing from 0.090 to 10 Pa•s over the investigated shear rate range.

but it is disturbed in guar solutions. This can be found is concordance with information identified in the studied [6, 7] The rheology of biopolymer mixes without added content of salt is illustrated as the the show in "Figures 12 and 13," This information was evaluated at two different concentration and heat extremes. "Figure 12, "illustrates that at lower temperatures, or 20°C, synergism is only somewhat more prevalent but not significantly so at higher polymer concentrations, like 2400 ppm, Nevertheless, no synergism was seen at lower polymer concentrations, such as 400 ppm; when the percentage of xanthan in the solution rose, the mixture's viscosity also rose.It goes without saying that the absence of lower polymer synergism concentrations and the diminished impact synergism at higher.

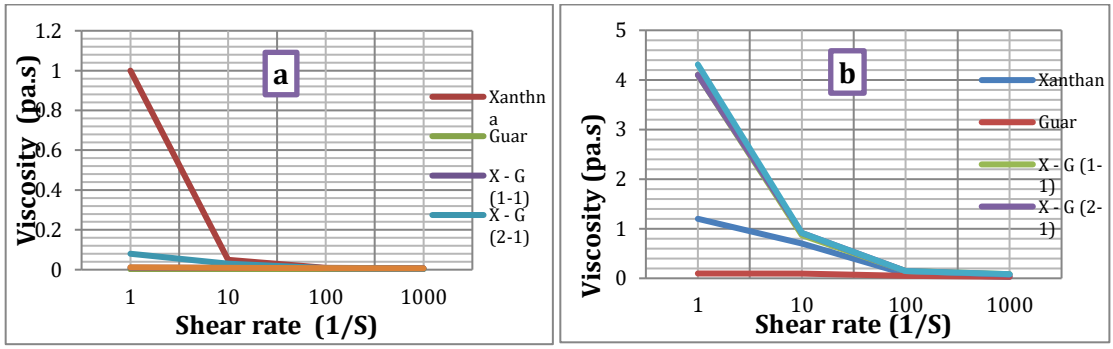


Figure 12: Rheology of combinations of xanthan and guar at 20°C and without brine. (a)The total concentration of solution is 400 ppm (b) the total concentration of solution is 2400 ppm.

The results shown in "Figure 12," indicate that the viscosity of xanthan,guar gum and mix ration solutions , without brine. At 400 ppm of xanthan solution have high valueof viscosity ranges from 0.001 to 1 Pa.s across different shear

rates,at 2400 ppm with 20 °C the viscosity is significantly higher, increasing from 0.005 to 4.2 Pa.s over the investigated shear rate range.

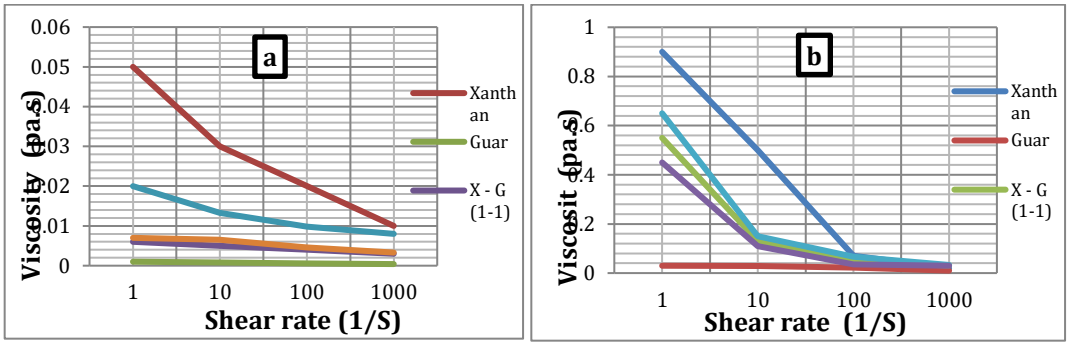


Figure 13: Rheology of combinations of biopolymer at 80°C and without brine. (a)The total concentration of solution is 400 ppm (b) The total concentration of solution is 2400 ppm.

The results shown in "Figure 13," indicate that the viscosity of xanthan,guar gum and mix ration solutions, without brine. At 400 ppm with 80 ºC of xanthan solution have high valueof viscosity ranges from 0.01 to 0.05 Pa•s across different shear rates,at 2400 ppm with 80 °C the viscosity is significantly higher, increasing from 0.005 to 0.9 Pa.s over the investigated shear rate range.

The FTIR spectrum, which is not displayed here, suggests that the polymer concentration is due to the way the compound xanthan gum is chemically structured. where a number of wave is 1725 cm^{-1} indicated the presence of an acetyl group. As illustrated in' Figure 13,", at higher temperatures, it wasn't detect synergism On either of these two extreme of the polymer concentration. "Figures 14 and 15," plot how the addition of salt affects the rheology of xanthan/guar combinations. As shown in" Figure 14a,", At all mixing ratios, xanthan and biopolymer combinations dramatically reduce viscosity. whereas purity of guar viscosity raise In large part up on adding 30% of content of salt in contrast with the kind of pure guar that hasn't been salted (show in "Figure 12,"). As illustrated in"Figure 14b," the decrease in viscosity that occurs when 30% salt is added to xanthan and biopolymer mixes is obviously observed at higher polymer concentrations, i.e., 2400 ppm. The higher guar concentration in the combination indicates that the xanthan to guar ratio of 1:2 has a greater viscosity compared to pure xanthan. It is also possible to see that, when the xanthan ratio in the mixture is high and at lower shear rate values, different synergism is seen, indicating that the composite has less viscosity than pure polymers. At higher temperatures, similar behavior was noted, as illustrated in "Figure 15,". To some extent, polymer adsorption in petroleum reservoirs is preferred because it decreases the area available for flow, which lowers water permeability and enhances the mobility ratio while also boosting oil output. Physical forces like Vander Waals forces cause polymer molecules to stick to grain surfaces when they come into contact with a solid surface, leading to polymer adsorption and retention. By injecting the polymer solution into a consolidated core sample and detecting the concentration of the polymer in the core effluent, polymer adsorption may be dynamically evaluated. Examining polymer adsorption and, thus, the effectiveness of polymer flooding requires two key elements. The ratio of water mobility to polymer solution mobility at equivalent temperature and fluid saturation conditions is known as the resistance factor (RF).

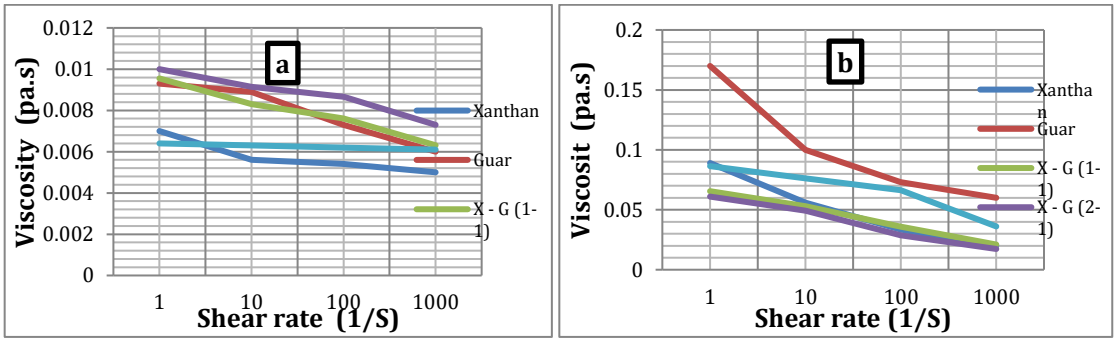


Figure 14: Illustrates Salt concentration has an effect on the rheology of xanthan and guar mixtures at 20°C and 30%. (a) The total concentration of solution is 400 ppm (b) The total concentration of solution is 2400 ppm.

The results shown in “Figure 14,” indicate that the viscosity of xanthan,guar gum and mix ration solutions at 20 oC , without brine. At 400 ppm of 33 % of xanthan and 66% of guar gum solutions have high valueof viscosity ranges from 0.007 to 0.01 Pa•s across different shear rates.at 2400 ppm ,the guar gum solution viscosity is significantly higher, increasing from 0.065 to 0.17 Pa•s over the investigated shear rate range .The rock's resistance to the flow of water injected after the polymer solution is described by the second component, the residual resistance factor (RRF). In order to help minimize water fingering caused by water injection after polymer flooding, this component provides a measurable indicator of the reduction in water permeability.

The following formats can be used to express these two terms:

$$RF = \frac{\Delta P(\text{polymer})}{\Delta P(\text{brine before polymer})} \quad (1)$$

$$RRF = \frac{\Delta P(\text{brine after polymer})}{\Delta P(\text{brine before polymer})} \quad (2)$$

Where : ΔP represents the pressure drop.

RF : Resistance Factor

RRF: Residual Resistance Factor

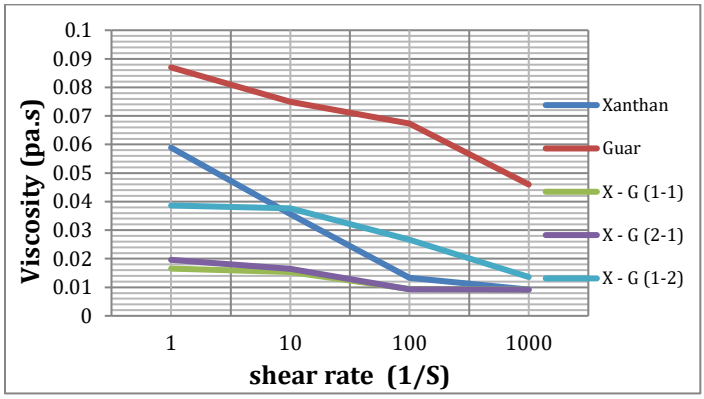


Figure 15: The impact of brine on the rheology of biopolymer combinations at 80°C .

The concentration of brine is 30%; the mixture's overall concentration is 2400 ppm.

Table 2: Data on displacement for a solution of biopolymer at 80°C and 15% salinity.

Sample	Polymer solution	RF	RRF
1	Xanthan (1200)	256	170
2	Xanthan (2400)	1253.4	654
3	Guar (1200)	19.7	15.9
4	Guar (2400)	165.9	97.8

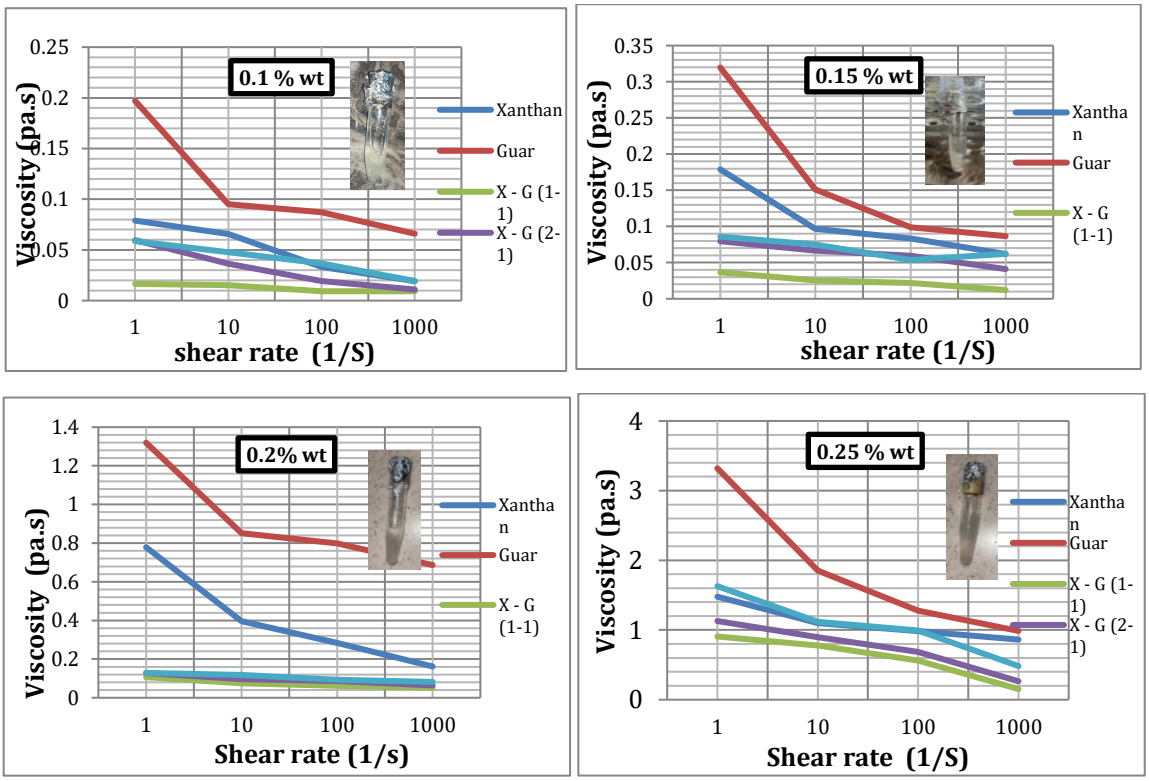
The results shown in “Figure 15,” indicate that the viscosity of xanthan,guar gum and mix ration solutions at 80 °C , 30% brine. At 2 400 ppm of 66 % of xanthan and 33 % of guar gum solutions have low value of viscosity ranges from 0.01 to 0.02 Pa•s across different shear rates.at 2400 ppm ,the guar gum solution viscosity is significantly higher, increasing from 0.045 to 0.088 Pa•s over the investigated shear rate range .“Table 2,” displays displacement data for guar & xanthan solutions obtained at 80 °C with 15% salinity and 1200 and 2400 ppm of polymer. In general, both the increase in the layer development of adsorbed polymers at the rock grain surfaces and the decrease in water mobility brought on by polymeric fluids are responsible. As shown in “Table 1,” this trend became apparent in our investigations when the biopolymer concentrations were increased from 1200 to 2400 ppm. At the same concentration, using xanthan solutions resulted in higher RF and RRF than using guar solutions. Thus, given the experimental conditions used, xanthan may lead to increased adsorption on the rock surface even at low concentrations, providing advantageous features for controlling water production.

The size of the polymer droplet in relation to the rock pore determines its ability to seal high permeability pores in the reservoir rocks in the “Table 3,”is the one of sample of rock sandstone. The RF and RRF will rise if a polymer droplet larger than the pore size of the rock clogs the pore and expands the shut-off zones inside the rock surfaces. The only way to control the rheology of the polymer solution is to mix the appropriate ratios of xanthan and guar at the same total polymer concentration. consequently, the master particle size in line with the pore size of the rock, as seen in “Figure 15,’. In immiscible polymer blends, quantity and relative viscosity both affect the average particle size.

Table 3 : The Properties of Core Sample.

Property	Core sample
Length, cm	8.5
Diameter, cm	3.81
Porosity, %	22.59
Permeability, mD	489.76
Pore Volume, ml	21.88

The current study technique has the advantage of being able to alter the viscosity of the polymer solution, which requires no increase in polymer concentration to alter the morphology of the polymer droplet in an aqueous environment at high temperatures and salinities. As illustrated in Figure 10, a high quantity of salt significantly reduces the shear viscosity of xanthan solution. Combining xanthan and guar at the same total polymer concentration allows one to control the particle size appropriate for sealing off the rock's pores in this situation by adjusting the viscosities of the polymer solution. A considerable portion of the polymer held was not pulled by the brine injection, which was meant to shift the polymer front across the core samples, as seen by the larger residual resistance factor value achieved when flooding with low polymer solutions (1200 ppm guar or xanthan).



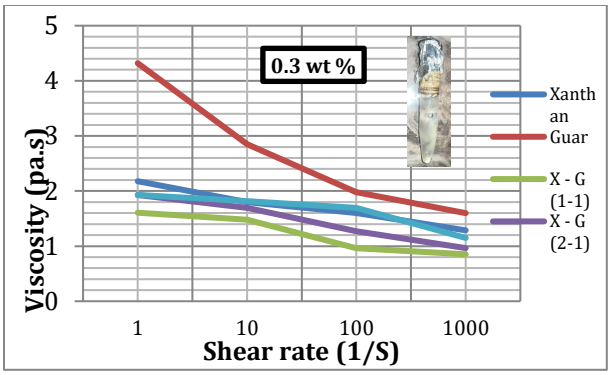


Figure 16: The impact of brine on the rheology of xanthan/guar combinations at 80°C. The concentration of brine is 30%; the mixture's overall concentration is 2400 ppm with different concentration of ZNO (0.1%,0.15%,0.2%,0.25%,0.3%)

The results shown in "Figure 16," indicate that the viscosity of xanthan,guar gum and mix ration solutions at 80 ºC , 30% brine with 0.3wt % . At 2400 ppm of guar gum solutions have high value of viscosity ranges from 1.8 to 4.3 Pa•s across different shear rates.at 2400 ppm with 0.3wt % ,the 50 % of guar gum and 50% of xanthan solutions viscosity is significantly lower, increasing from 0.01to 0.02 Pa•s over the investigated shear rate range.The rheological analysis of xanthan/guar mixtures at 2400 ppm under 30% brine and 80°C shows that,extreme salinity and high temperature significantly weaken the fluid's viscosity and structural integrity, particularly due to polymer coil collapse and thermal thinning .the addition of ZnO nanoparticles provides a stabilizing effect, increasing viscosity by enhancing polymer-particle interactions and potentially restoring network structure.the most effective zno concentration is observed at 0.3%, where the maximum viscosity is reached, indicating an optimal level of nanoparticle dispersion and network reinforcement.
Increasing zno beyond this optimal point (0.25% and 0.3%) results in diminished returns or slight viscosity reduction, likely due to agglomeration of particles or saturation effects that limit polymer-nanoparticle synergy.

Table 4: Data on displacement for a solution of biopolymer at 80°C and 15% salinity with 0.3 % wt of zinc oxide nanoparticle.

Sample	Polymer solution (ppm)	RF	RRF
1	Xanthan (1200)	307.2	204
2	Xanthan (2400)	1504.08	784.8
3	Guar (1200)	23.64	19.08
4	Guar (2400)	199.08	117.36

In the "Table 4," the addition of 0.3 wt% zinc oxide (ZNO) nanoparticles to bio - polymer solutions at 80°C and 15% salinity significantly enhances their displacement efficiency and permeability reduction capabilities .Resistance Factor (RF) and Residual Resistance Factor (RRF) increased by approximately 20% compared to polymer solutions without nanoparticles .This improvement is attributed to,enhanced viscosity and flow resistance due to nanoparticle–polymer interactions.Improved thermal and salinity stability of the polymer solutions. Better pore plugging and retention behavior due to nanoparticle presence. Incorporating Zno nanoparticles into polymer flooding formulations greatly improves their performance under high-temperature, high-salinity conditions, making them more effective for enhanced oil recovery (EOR) applications.

4 Conculsion

In this study systematically investigated the rheological behavior of xanthan, guar, and their binary mixtures under varying polymer concentrations, salinity levels, and nanoparticle addition, with a particular focus on enhanced oil recovery (EOR) applications in high-salinity reservoirs. The results demonstrate that xanthan solutions exhibit higher shear viscosity than guar solutions; however, xanthan is more sensitive to salinity, experiencing a pronounced viscosity reduction as salt concentration increases. In contrast, guar-rich systems showed greater tolerance to salinity, enabling partial compensation for viscosity loss in mixed polymer formulations.The combination of xanthan and guar was shown to be an effective strategy for tuning solution rheology without increasing total polymer concentration. Although synergistic effects were only observed at high total polymer concentrations (2400 ppm), the mixed systems

provided improved rheological control across a wide range of salinity conditions. This rheological tunability is particularly advantageous for EOR operations, as it allows adjustment of the effective hydrodynamic size of polymer aggregates to enhance pore-scale plugging and mobility control, especially in high-permeability water-producing zones. Moreover, the incorporation of 0.3 wt% zno nanoparticles into selected guar/xanthan mixtures led to a significant enhancement in flow resistance, with resistance factor (RF) and residual resistance factor (RRF) increasing by approximately 20% compared to nanoparticle free systems. This improvement highlights the potential of zno biopolymer nanocomposites as efficient shut-off agents for extreme salinity reservoirs ,with 2400 ppm of xanthan the RF and RRF have great value 1504.08 and 784.8 , and with 1200 ppm of guar guam the RF and RRF have low value 23.64 and 19.08.

Future work should focus on evaluating the long-term thermal and chemical stability of these biopolymer–nanoparticle systems under reservoir conditions, as well as conducting core flooding experiments in heterogeneous and fractured media. Additionally, investigating alternative nanoparticle types, polymer ratios, and in-situ gelation mechanisms could further optimize these formulations for field-scale EOR deployment.

Table of Symbols

Symbol	Definition
ppm	Parts per million
RF	Resistance Factor
RRF	Residual Resistance Factor
S^{-1}	Inverse Second
Pa.s	Pascal * Second
EOR	Enhanced Oil Recovery

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Authors contribution

Mohammed Khairy M.Salih conducted the experimental work, performed data analysis, and prepared the original draft of the manuscript.
Sherwan M. Simo contributed to the study design, supervised the research work, and reviewed and edited the manuscript.
Abbas Khaksar Manshad contributed to data interpretation, provided scientific guidance, and critically revised the manuscript.All authors read and approved the final version of the manuscript.

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