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INVESTIGATION OF THE POTENTIAL OF ENVIRONMENTALLY FRIENDLY NON-IONIC SURFACTANTS FOR EOR

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ABSTRACT. This study investigates the use of non-ionic surfactants synthesized from sunflower oil as sustainable alternatives for enhanced oil recovery (EOR). The bio-based surfactants were evaluated alongside commercial products through physicochemical and performance tests. The results revealed that the renewable formulations demonstrated excellent oil displacement and emulsification capacity, comparable to or exceeding that of conventional surfactants. These findings highlight the potential of plant-derived surfactants to reduce the environmental impact of EOR processes without compromising efficiency.

Keywords: *enhanced oil recovery, sustainability, environmentally friendly, non-ionic surfactant.*

INTRODUCTION

In addition to meeting the increasing global energy demand, environmental protection has become an increasingly critical priority. Balancing these two often conflicting objectives poses significant challenges for professionals in the field of engineering. According to current forecasts, the world's energy supply will continue to rely predominantly on crude oil-based sources, making it essential to develop more environmentally friendly technologies for oil extraction.

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The continuous growth in global energy consumption has intensified the need for more efficient exploitation of existing petroleum reserves. One of the most effective strategies in this regard is Enhanced Oil Recovery (EOR), a technique employed when conventional primary and secondary recovery methods are no longer capable of extracting the residual oil trapped within the pore spaces of reservoir rocks [1]. In such cases, the injection of auxiliary substances becomes necessary to alter the properties of the reservoir fluids and improve oil mobility and recovery efficiency [2].

The fundamental principle of EOR lies in the ability of the injected agents to disrupt the physicochemical forces that retain oil within the porous matrix of the reservoir. By modifying these interactions, the mobility of the trapped oil increases, enabling more effective displacement towards production wells [3].

A wide range of EOR techniques exists, which are typically categorized based on the type of agent applied. These include thermal methods, gas injection processes, chemical techniques, and other additive-based approaches. The selection of a suitable EOR strategy is influenced by various factors, such as the geological characteristics of the reservoir, the physical and chemical properties of the crude oil, and the composition of formation water [4–6]. A classification of EOR methods is illustrated in Figure 1 [7].

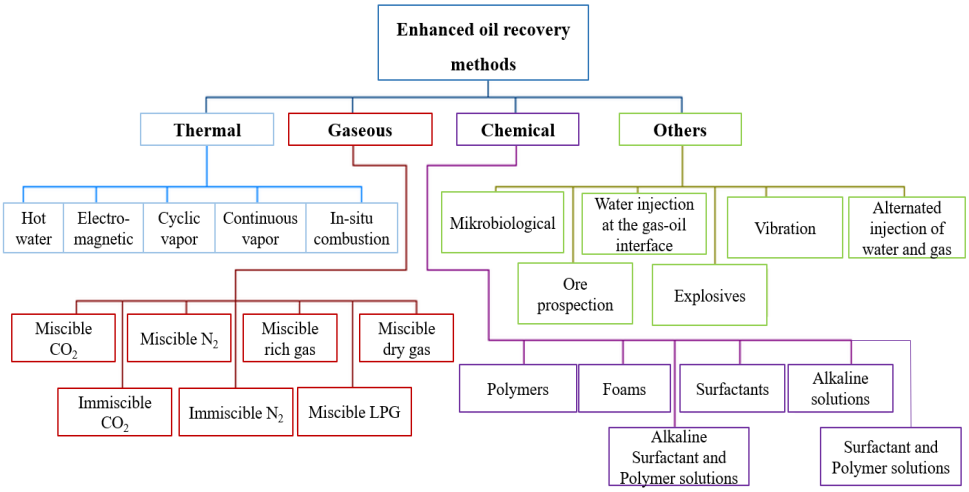

Figure 1. Additives used in enhanced oil recovery processes

The next phase of this research focuses on the investigation of surfactants used in chemical enhanced oil recovery (cEOR) processes. As shown in Figure 1, various chemical agents are commonly employed in cEOR techniques, including polymers, surfactants, alkaline substances, and

foaming agents [8]. While each of these additives can be effective on its own, their combined application may result in synergistic effects, further improving oil recovery efficiency.

This study focuses on the development and comprehensive evaluation of environmentally friendly, plant-based non-ionic surfactants for Chemical Enhanced Oil Recovery (CEOR) applications. The primary objective is to synthesise and evaluate alternative surfactant formulations derived from renewable resources in order to reduce the environmental footprint of EOR operations. In addition to their green origin, these novel surfactants were tested for a wide range of physicochemical properties including solubility, pH, viscosity, pour point and transmittance. In addition, their functional performance was investigated through oil displacement, emulsification and interfacial tension (IFT) tests under reservoir relevant conditions. The aim is to identify sustainable surfactant candidates that can match or exceed the performance of conventional fossil-based products, while offering improved environmental performance and process stability. This work contributes to ongoing efforts to align oil recovery technologies with the principles of green chemistry and sustainable engineering.

RESULTS AND DISCUSSION

In the following, the measured physical and chemical properties of the tested surfactants are presented. The results are summarized in **Table 1.**

Table 1. Physical and chemical properties of the investigated surfactants

Properties/ Sign of surfactant		S1	S2	S3	S4	REF1
Density (g/cm^3)	40°C	0.9800	0.9860	1.2201	1.0032	1.2223
Dynamic viscosity (mPas)	40°C	450	1285	1.6570	0.74264	1.5947
pH value		9.74	not measurable	12.83	11.83	8.89
Pour point (°C)		9	1	-15	-16	<-90*
Solubility		partially soluble	non-soluble	soluble	soluble	soluble
Transmittancy (%)		51	69	23	28	82
Water number (cm^3)		13.5	4.30	13.0	11.65	11.25

*In this case, the pour point was determined on the manufacturer's SDS sheet [9].

In all cases, the acid value was in the alkaline range and in the case where it was not measurable (S2), the acid value in **Table 2** also indicates that the substance is alkaline in nature.

The value of the water number is higher than 10 for all the samples tested, except for S2, indicating that the substance is soluble in water.

Table 2. Results of the impact assessments of the investigated surfactants

Properties/Sign of surfactant	S1	S2	S3	S4	REF1
Oil displacement test, (mm)	12	10	26	20	20
Emulsifying (solubilising) effect test, (V/V% emulsion)	22	23	41	63	100
IFT (mN/m)	8.67	10.2	7.14	5.3	1.82
Acid number	0	7.69	0	0	0.33
Turbidity value	688	>1100	1.93	3.42	11.16

The experimental results revealed that Sample-3 and Sample-4 exhibited favourable physicochemical properties, such as good solubility, high thermal stability (low pour points) and a pH ranging from neutral to alkaline. Their performance in impact-related tests was particularly noteworthy. Sample-3 achieved the highest oil displacement value (26 mm), outperforming both industrial and natural surfactants. Sample-4 demonstrated remarkable emulsifying capacity (63% V/V) and an interfacial tension (IFT) of 5.3 mN/m, lower than that of most of the tested surfactants, except REF1.

The industrial reference surfactant (REF1) demonstrated excellent performance in terms of IFT (1.82 mN/m) and emulsification (100% V/V). However, its environmental credentials could not be verified due to a lack of information on the origin of the raw materials. While partially plant-derived, SPAN80 and Empilan 2502 showed limited performance: SPAN80 had the highest acid number and turbidity, and both commercial biosurfactants displayed significantly lower oil displacement and emulsifying capabilities than the experimental samples.

Ultimately, of the surfactants tested, S2 was inferior to the others in terms of water solubility and in the impact studies. Despite having a pH in the alkaline range and being largely dissolved by mixing, surfactant S1 has a high transmission and turbidity and is also below the reference surfactant in terms of impact studies. The pH of surfactants S3 and S4 is in the alkaline range, and they are soluble in water with minimal mixing, with a water number above 11 in both cases, which is also related to water solubility. In the impact tests, similar or better results than the reference were obtained. Based on the properties tested and the results obtained, I establish the following ranking in **Table 3**.

Table 3. Ranking of the investigated surfactants

Rank	Sign of surfactant	Name of surfactant
1.	S4	Sample-4
2.	S3	Sample-3
3.	S1	EMPILAN 2502
4.	S2	SPAN80

CONCLUSIONS

This study investigated the potential use of environmentally friendly, plant-based, non-ionic surfactants in chemical enhanced oil recovery (CEOR) processes. Five surfactants were evaluated: three commercial products (REF1, Empilan 2502 and SPAN80) and two experimental samples synthesised from sunflower oil (Sample-3 and Sample-4). The evaluation covered a wide range of physical, chemical and performance parameters relevant to the applicability of EOR.

It is important to note that this study did not include a full environmental impact assessment. Therefore, no conclusions can be drawn on the overall environmental impact of the tested surfactants. However, the use of renewable raw materials in the synthesis of Sample-3 and Sample-4 suggests a potential for improved sustainability, pending further life cycle or biodegradability analysis.

In conclusion, the results indicate that the experimental plant-based surfactants, particularly Sample-3 and Sample-4, have competitive physicochemical profiles and functional properties that support their application in EOR. Future work should focus on structural optimisation to further improve performance, as well as conducting core flooding tests, long-term stability evaluations and comprehensive environmental impact assessments to confirm their suitability for industrial use.

EXPERIMENTAL SECTION

Raw Materials

This paper presents the results of an experimental study examining the physical, chemical, and functional properties of several plant-based non-ionic surfactants. The investigated materials include 2,4,7,9-tetramethyl-5-decyne-4,7-diol, which is the active substance in Surfynol 440 [10-12], hereafter REF1; Empilan 2502, derived from coconut fatty acid [13]; SPAN80, an oleic acid-based surfactant supplied by Sigma-Aldrich [14]; and two experimental surfactants synthesized from sunflower oil, designated as Sample-3 and Sample-4.

The REF1 non-ionic surfactant was tested for comparison as it is used in industry. Its raw material is not known to be environmentally friendly.

The surfactants listed in **Table 4** were subjected to a comprehensive set of laboratory tests to assess their physicochemical characteristics and potential applicability in Enhanced Oil Recovery (EOR) processes. All substances under investigation belong to the non-ionic surfactant category.

Table 4. Investigated surfactants and their environmentally friendly base materials

Sign of surfactant	**S1**	**S2**	**S3**	**S4**	**REF1**
Name of surfactant	**Empilan 2502**	**SPAN80**	**Sample-3**	**Sample-4**	**-**
Raw material	coconut fatty acid	sorbitol	sunflower oil	sunflower oil	-
Distributor	Huntsman	SigmaAldrich	University of Pannonia	University of Pannonia	SigmaAldrich

The plant oil-based surfactants developed in this study are non-ionic in nature. The synthesis pathways of the experimental surfactants described below follow a similar approach, with the main difference being the carbon chain length of the connecting spacer molecules. In both cases, a dibromoalkane compound was used for the linkage.

The first step of the synthesis involved the transesterification of vegetable oil with glycerol to produce a glycerol ester intermediate. In the second step, this intermediate was reacted with a dibromoalkane in an alkaline environment using a phase-transfer catalyst. The reactions were carried out at temperatures ranging from 80 to 250°C under atmospheric pressure. The resulting products were dried using anhydrous sodium sulphate [15].

Methodology: To assess the suitability of the investigated surfactants for chemical enhanced oil recovery (CEOR), a comprehensive series of physicochemical and performance evaluations was conducted. These tests aimed to determine key parameters that influence the efficiency, stability, and environmental compatibility of surfactants in reservoir conditions.

pH value: The pH of the surfactant solutions was measured in a 5 g/L aqueous solution prepared with distilled water, using a SevenCompact Duo pH meter (Mettler Toledo). The pH indicates the chemical stability of the surfactant and its potential interactions with reservoir fluids, as extreme pH values can adversely affect formation integrity and equipment.

Density and dynamic viscosity: Density and dynamic viscosity were measured at 40°C using an SVM 3000 Stabinger Viscometer. These parameters affect fluid flow, injectivity, and mobility control during CEOR operations.

Solubility: The water solubility of the surfactants was evaluated in 5 g/L aqueous solutions prepared with distilled water. Solubility was assessed through visual inspection and transmittance measurements. Transmittance was determined in 645 nm, using an Avantes AvaSpec-DUAL spectrophotometer (0% completely cloudy, 100% transparent). Good water solubility and high transparency are indicators of efficient dispersion in brine and reduced risk of phase separation in the reservoir.

Pour point: The pour point of the surfactants was determined using a Koehler automatic pour point and freezing point analyzer. A low pour point is essential to ensure injectivity and operational stability under varying field temperatures.

Water number: This test is used to assess the hydrophilic–lipophilic balance of surfactant compounds, providing insight into their emulsifying capabilities and salt tolerance. The water number was determined by titration. For the measurement, 1 g of surfactant was dissolved in 30 cm^3 of a 4:96 (V/V) cyclohexane–acetone mixture and titrated with distilled water until the onset of turbidity was observed [16].

Oil displacement test: The oil displacement test was performed using a thin film chromatography method. Glass plates coated with Algyő grained rock powder and crude oil droplets were immersed in 5 g/L surfactant solutions prepared with filtered brine. After 3 hours at 60 °C, the displacement distance of the oil was measured to evaluate surfactant efficiency [17]

Emulsifying (solubilising) effect test: The emulsifying capacity of the surfactants was tested using an ADEM automatic emulsibility tester in crude oil–brine systems. Equal volumes (40 cm^3) of 5 g/L surfactant solution and Algyő 892 crude oil were mixed at 1500 rpm, then left to rest for 30 minutes. Emulsion stability and extent were evaluated under controlled conditions [18].

Interfacial tension test: Interfacial tension (IFT) was measured using a Krüss SDT Spinning Drop tensiometer with Algyő 892 crude oil and 5 g/L surfactant solutions in filtered brine. The droplet radius was used to calculate IFT, providing insight into the surfactants' effectiveness in modifying oil–water interfaces for EOR optimization [19]

Acid number: The acid number was determined by titration with standardized KOH solution using phenolphthalein as an indicator. The required KOH volume was used to calculate the acid content (mg KOH/g sample), providing information on the sample's chemical quality and processing suitability [20].

Turbidity value: Turbidity was measured using a WTW Turb 430IR handheld turbidimeter. The turbidity value is expressed in NTU (Nephelometric Turbidity Unit). For each sample I tested a solution of 5g/L in filtered brine from Algyő.

By combining these analyses, a detailed profile of each surfactant's performance and compatibility with reservoir conditions was obtained, ensuring that the most promising candidates could be identified for sustainable CEOR applications.

Table 5 summarises the measurement methods used and their associated standards.

Table 5. Measurements and related standards

Measurement	Method Description	Relevant Standard(s)
pH value	5 g/L aqueous solution, measured with a pH meter (Mettler Toledo)	ISO 10523, ASTM D1293
Density and viscosity	Measured at 40 °C using SVM 3000 Stabinger Viscometer	ASTM D7042 (dynamic), ASTM D445, ISO 12185
Solubility & transmittance	Visual and spectrophotometric assessment (645 nm)	No standard; method based on literature protocols
Pour point	Measured with Koehler automatic analyzer	ASTM D97, ISO 3016
Water number	Titration until turbidity in cyclohexane–acetone mixture	No international standard; in-house/literature-based
Oil displacement test	Thin-film method using rock powder and crude oil on glass plates	No international standard; literature-based protocol
Emulsifying capacity	ADEM automatic tester, crude oil–brine system, 1500 rpm stirring, 30 min settling	Related: ASTM D6084, ISO 6614 (partially applicable)
Interfacial tension (IFT)	Spinning drop method with Krüss SDT tensiometer	DIN 55681 (spinning drop), ASTM D971, ISO 6889
Acid number	Titration with standardized KOH, phenolphthalein indicator	ASTM D664, ISO 6618
Turbidity	Measured with WTW Turb 430IR turbidimeter (infrared method)	ISO 7027, EPA 180.1

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REFERENCES

1. A. O. Gbadamosi; R. Junin; M. A. Manan; Int. Nano Lett., 2019, 9, 171–202.
2. W.-L. Kong; B.-B. Zhang; M. Issakhov; M. Gabdullin; Pet. Sci., 2022, 19(4).
3. B. N. Barman; V. L. Cebolla; A. K. Mehrotra; C. T. Mansfield; Pet. Coal, 2001, 73, 2791–2804.
4. A. Agi; R. Junin; M. F. Syamsul; A. S. Chong; A. Gbadamosi; Petroleum, 2019, 5(1), 42–51.
5. A. Gbadamosi; S. Patil; M. S. Kamal; A. A. Adewunmi; A. S. Yusuff; A. Agi; J. Oseh; Polymers, 2022, 14, 1433.
6. O. Tavakkoli; H. Kamyab; M. Shariati; A. M. Mohamed; R. Junin; Fuel, 2022, 312.
7. A. Gurgel; M. C. Moura; T. N. D. Castro; E. L. Barros Neto; A. A. Dantas Neto; Braz. J. Pet. Gas, 2008, 2.
8. A. Samanta; A. Bera; K. Ojha; J. Pet. Explor. Prod. Technol., 2012, 2, 67–74.
9. National Center for Biotechnology Information; PubChem Compound Summary for CID 16213030, 2,4,7,9-Tetramethyl-5-decyne-4,7-diol ethoxylate; https://pubchem.ncbi.nlm.nih.gov/compound/2_4_7_9-Tetramethyl-5-decyne-4_7-diol-ethoxylate; accessed May 19, 2025.
10. E. Sansonetti; B. Andersons; I. Andersone; Mater. Sci. Eng., 2016, 111.
11. R. Krishnan; R. Sprycha; Colloids Surf., 1999, 149, 355–366.
12. M. D. Mampaey; Liquid Absorption into Porous Media; Master's Thesis, Eindhoven University of Technology, Netherlands, 2022.
13. J. Perkowski; W. Jozwiak; L. Kos; P. Stajszczyk; Fibres Text. East. Eur., 2006, 59(5), 114–119.
14. K. Kato; P. Walde; N. Koine; S. Ichikawa; T. Ishikawa; R. Nagahama; T. Ishihara; T. Tsujii; M. Shudou; Y. Omokawa; T. Kuroiwa; Langmuir, 2008, 24(19), 10762–10770.
15. N. Pal; N. Kumar; A. Verma; K. Ojha; A. Mandal; Energy Fuels, 2018, 32, 11344–11361.
16. M. Hartyányi; R. Nagy; L. Bartha; S. Puskás; Energies, 2024, 17, 2438.
17. M. Hartyányi; R. Nagy; R. Bejczi; L. Bartha; S. Puskás; Energy Sci. Eng., 2025.
18. M. Hartyányi; R. Bejczi; R. Nagy; N. Demcsák; L. Bartha; S. Puskás; MethodsX, 2024, 12, 102671.
19. R. Nagy; R. Sallai; L. Bartha; Á. Vágó; Adv. Chem. Eng. Sci., 2015, 5, 121–128.
20. A. V. Molnár-Kiss; R. Nagy; Waste Biomass Valor., 2024, 15, 917–921.