

EFFECT OF β -CYCLODEXTRIN AND LACTIC ACID-BASED SUPRADES ON ASPHALTENE AGGREGATION PROCESSES

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Abstract. *Introduction.* Asphaltene precipitation and aggregation complicate petroleum production, transport, and refining. *Aim.* To evaluate β -cyclodextrin–L-lactic-acid SUPRADES as a modifier of asphaltene aggregation in model oil prepared from Karazhanbas crude oil. *Methods.* Asphaltenes were isolated according to GOST 11858-66. SUPRADES was prepared at a 1:60 molar ratio and characterized by FT-IR, UV–Vis, thermogravimetry, and ¹H and ¹³C NMR, including COSY, HMQC, and HMBC. *Results and discussion.* FT-IR indicated a hydrogen-bonded network, TGA revealed multistage decomposition, and NMR confirmed the lactic-acid fragment and its principal correlations. Near 292 nm, absorbance decreased from approximately 0.88 to 0.59 after SUPRADES addition, an apparent decrease of about 33%. Because replicate-level variability was unavailable, the comparison is semiquantitative. *Conclusion.* The system may modify asphaltene aggregation, but quantitative inhibition must be confirmed at defined concentrations with independent replicates.

Keywords: β -cyclodextrin, lactic acid, asphaltenes, aggregation, FT-IR spectroscopy, UV–Vis spectroscopy, SUPRADES

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1. Introduction

Prevention of asphaltene deposition is one of the key tasks of the petrochemical industry, since aggregation and subsequent flocculation lead to deposits that impair the transport and operational characteristics of oil. Asphaltene inhibitors can shift the onset of deposition and reduce both the amount of sediment formed and particle size. Nonionic surfactants capable of stabilizing asphaltene particles in a dispersed medium have proved effective in this regard. Historically, aromatic organic solvents such as toluene and xylene have been used because they dissolve asphaltene aggregates. However, their toxicity, volatility, and environmental impact significantly limit their use in modern processes. Alternative inhibitors therefore include nonionic surfactants and polymer additives that stabilize asphaltenes through peptization and prevent aggregation [1].

In recent decades, considerable attention has been paid to ionic liquids with physicochemical properties such as low volatility, high thermal stability, and structural tunability, making them promising candidates as asphaltene inhibitors [2]. Further development of this field led to deep eutectic solvents (DES), which combine efficiency with ease of preparation and relatively low cost; their combination with macrocyclic host molecules has opened additional opportunities for molecular recognition [3]. Supramolecular chemistry focuses on non-covalent interactions and molecular recognition mechanisms that form stable host–guest complexes [4]. In this context, supramolecular deep eutectic solvents (SUPRADES) were proposed in 2020 as an extension of the DES class. These systems are formed using cyclodextrins (CDs) or their derivatives together with hydrogen-bond donors, particularly carboxylic acids [5, 6]. This approach combines the advantages of DES with the selectivity and encapsulation ability of macrocyclic compounds. Cyclodextrin-based systems are especially widespread because of their natural origin, availability, low cost, and molecular-recognition properties [7]. β -Cyclodextrin is frequently used because its cavity size enables interaction with a broad range of organic molecules and it is economically accessible [8]. Depending on composition and synthesis strategy, CD-based SUPRADES can be classified as binary or ternary systems [9]. SUPRADES can retain high stability in aqueous media [10], although molecular-dynamics studies show that water can markedly affect their structure and dynamics [11]. Complementary host–guest interactions and hydrogen bonding govern the organization and functional properties of these systems and enable selective capture of molecules of suitable shape, size, and polarity [12]. Their versatility has also been demonstrated in analytical separations, including chiral capillary electrophoresis [13].

2. Experimental part

Asphaltene isolation. Asphaltenes were isolated from Karazhanbas crude oil (Western Kazakhstan) according to GOST 11858-66. The crude oil was treated

with n-hexane as the precipitant, allowed to stand for 24 h, and filtered without disturbing the settled phase. The filtration stage is shown in Figure 1.



Figure 1 – Asphaltene filtration from Karazhanbas oil.

Purification and recovery. The precipitate retained on the filter paper was subjected to Soxhlet extraction with toluene to separate the asphaltene fraction from co-extracted resins and oils. Toluene was refluxed at approximately 116 °C using an oil bath maintained at 120 °C. The extraction cycle was repeated 4–5 times. The recovered asphaltenes were dried at 100 °C for 24 h and then cooled to room temperature in a desiccator.

Model oil and SUPRADES treatment. The isolated asphaltenes were dissolved in toluene (purity $\geq 99.8\%$) at 0.5 wt%. The solution was stirred for 2 h and equilibrated for 24 h. SUPRADES was evaluated over the verified working concentration range of 100–1000 ppm, and the samples were magnetically stirred for 10–30 min. n-Hexane was then added at an n-hexane:model-oil ratio of 40:1, and the mixtures were left for 24 h at room temperature. The available experimental record did not retain the exact SUPRADES dose and mixing time linked to the representative spectrum in Figure 3; therefore, the UV–Vis result is reported as a semiquantitative comparison rather than as a concentration–response experiment.

Preparation of SUPRADES. SUPRADES was prepared by mixing β -cyclodextrin (98%, Macklin Biochemical Co., Ltd., China) and L-(+)-lactic acid ($\geq 85\%$, Macklin Biochemical Co., Ltd., China) at a 1:60 molar ratio [14]. The components were heated at 80 °C with continuous magnetic stirring at 350 rpm until a clear homogeneous liquid formed [15].

3. Results and discussion

3.1. Physico-chemical properties

In this work, the properties of pure lactic acid (LA), β -cyclodextrin (β -CD), and their mixture at a 1:60 molar ratio were considered. At 30 °C, pure LA has a density of approximately 1200 kg m⁻³ and a viscosity below 50 mPa·s. Pure β -CD is a crystalline solid with low water solubility, whereas contact with LA produces a liquid supramolecular deep eutectic solvent through extensive hydrogen bonding. The viscosity of β -LA is 111.74 mPa·s at 30 °C and decreases to approximately 40 mPa·s at 60 °C [14]. The density of β -LA was 1245 kg m⁻³ at 20 °C. Because the density values for pure LA and β -LA refer to different

temperatures, they are reported separately and are not used for direct quantitative comparison. At 25.5 °C, β -LA had a pH of 1.08 and an electrical conductivity of 26.5 mS cm⁻¹. The pH meter was calibrated with pH 4.00, 7.00, and 10.00 buffers. pH and conductivity measurements were performed in triplicate, and mean values were reported. Measurements were conducted at the stated temperatures and atmospheric pressure.

3.2. FT-IR spectroscopy

FT-IR spectroscopy was used to characterize β -cyclodextrin–lactic-acid SUPRADES (1:60) and to examine its interaction with components of the model oil. The corresponding spectra are shown in Figure 2.

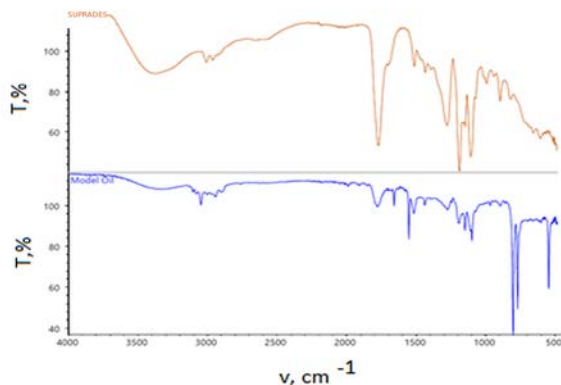


Figure 2 – FT-IR spectra of SUPRADES and model oil.

The broad band at 3300–3400 cm⁻¹ was assigned to O–H stretching and is consistent with extensive intermolecular hydrogen bonding between β -cyclodextrin hydroxyl groups and lactic-acid carboxyl groups. Bands at 2920–2950 cm⁻¹ were assigned to aliphatic C–H stretching. The band at approximately 1715–1720 cm⁻¹ corresponds to C=O stretching of the lactic-acid carboxyl group. C–H and O–H bending modes occur at 1450–1380 cm⁻¹. Intense bands at 1200–1000 cm⁻¹, particularly 1120–1030 cm⁻¹, were assigned to C–O–C and C–O stretching in the glucopyranose units of β -cyclodextrin, indicating retention of the cyclic carbohydrate framework. The model-oil spectrum contains bands at approximately 3030 cm⁻¹ (aromatic C–H), 2920 and 2850 cm⁻¹ (aliphatic C–H), approximately 1600 cm⁻¹ (aromatic C=C), and 1000–700 cm⁻¹ (out-of-plane aromatic C–H bending). Taken together, these data are consistent with formation of a hydrogen-bonded SUPRADES system containing functional groups capable of interacting with polar and aromatic asphaltene fragments; FT-IR alone, however, does not prove a specific host–guest complex.

3.3. UV–Vis spectroscopy

Representative UV–Vis spectra of the model oil without and with SUPRADES were compared over the 200–800 nm range shown in Figure 3. The available record did not include the spectrophotometer model, optical path length,

or replicate-level acquisition metadata; therefore, no unverified instrumental details were added.

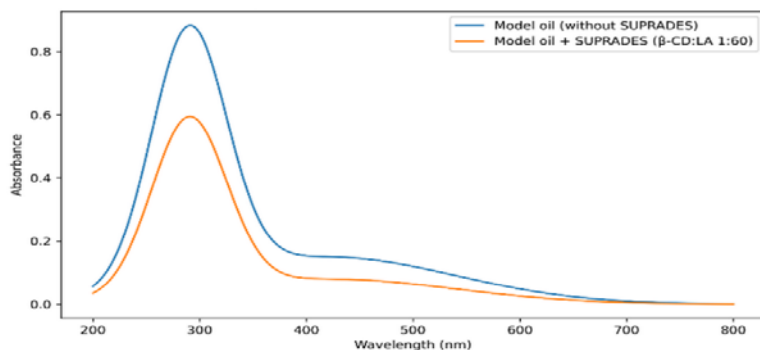


Figure 3 – Representative UV–Vis spectra of model oil without and with SUPRADES.

Both representative spectra show a maximum near 292 nm, associated with the optical response of aromatic asphaltene structures. From the plotted curves, the absorbance decreased from approximately 0.88 for the model oil without SUPRADES to approximately 0.59 after SUPRADES addition. The apparent relative absorbance decrease, calculated as $(0.88 - 0.59)/0.88 \times 100\%$, was approximately 33%. This value describes the optical change in the plotted spectra and should not be interpreted as a statistically validated aggregation-inhibition efficiency. Replicate-level raw spectra and variability estimates were unavailable; consequently, standard deviations, error bars, and inferential significance are not reported. Under otherwise comparable sample preparation, the lower absorbance is consistent with reduced aggregation or dispersion of asphaltene-containing structures. Hydrogen bonding between polar asphaltene fragments and the hydroxyl/carboxyl groups of SUPRADES, together with possible host–guest interactions involving the β -cyclodextrin cavity, may contribute to this behavior, but these mechanisms require independent confirmation.

3.4. Thermogravimetric analysis

Thermogravimetric analysis (TGA) was performed to assess the thermal stability of the synthesized supramolecular deep eutectic solvent based on β -cyclodextrin and lactic acid (β -CD:LA, 1:60). This method makes it possible to determine the temperature ranges of thermal decomposition, as well as to establish the resistance of the resulting system to thermal effects. The study of the thermal behavior of SUPRADES is an important step to assess the possibility of its practical application in petrochemical processes, since asphaltene deposition inhibitors must maintain stability at elevated temperatures of oil transportation and refining. The resulting TG curve is shown in Figure 4.

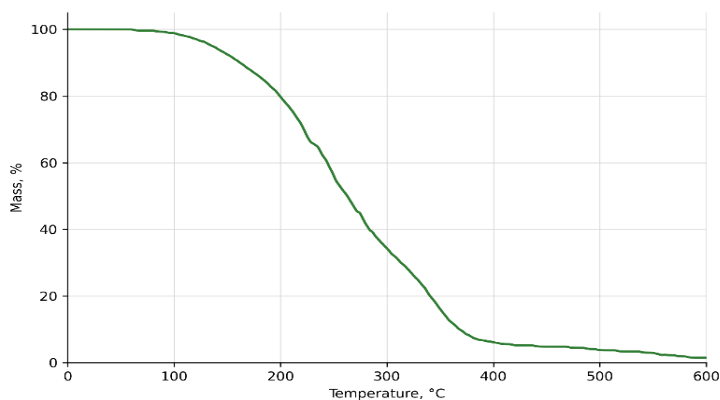


Figure 4 – TG curve of SUPRADES.

The TG curve shows multistage mass loss. The initial loss at approximately 40–120 °C is attributed to physically adsorbed moisture, water in the β -cyclodextrin cavity, and possible evaporation of weakly bound lactic acid. At approximately 120–220 °C, mass decreases as weak intermolecular interactions and the hydrogen-bonded network are disrupted. The main decomposition step at approximately 230–350 °C is assigned to β -cyclodextrin degradation and cleavage of glycosidic bonds. Above approximately 400 °C, the remaining organic fragments decompose and a carbonaceous residue forms. The curve indicates that major decomposition accelerates above approximately 200 °C; therefore, the material may warrant further evaluation under lower-temperature petrochemical conditions, but application stability should be confirmed under process-specific conditions.

3.5. NMR analysis of SUPRADES

The ^1H and ^{13}C NMR spectra were recorded on a JEOL JNM-ECA 400 spectrometer at 399.78 and 100.53 MHz, respectively, using D_2O as the solvent. Chemical shifts were referenced to the residual solvent signal. In the ^1H NMR spectrum of SUPRADES, the methyl protons H-3 of lactic acid appeared as a three-proton multiplet at 0.95–0.96 ppm, while the methine proton H-2 appeared as a one-proton multiplet at 3.89–3.95 ppm. The hydroxyl proton H-1 and carboxyl proton H-6 were not observed because of rapid proton/deuterium (H/D) exchange with D_2O . The low concentration of β -cyclodextrin did not allow its signals to be identified in solution. The ^1H – ^1H COSY spectrum showed a correlation between the methyl (H-3) and methine (H-2) protons. In the ^{13}C NMR spectrum, lactic-acid carbon signals were observed at 19.11 ppm (C-3), 66.14 ppm (C-2), and 177.86 ppm (C-4). The ^1H – ^{13}C HMQC correlations confirmed direct one-bond connections H-3/C-3 (0.95, 19.09 ppm) and H-2/C-2 (3.91, 66.06 ppm). The ^1H – ^{13}C HMBC spectrum showed long-range correlations H-3/C-2 (0.95, 66.61 ppm), H-3/C-4 (0.95, 178.16 ppm), H-2/C-3 (3.90, 19.18 ppm), and

H-2/C-4 (3.90, 178.16 ppm). The ^1H spectrum is presented in Figure 5, and the ^{13}C spectrum in Figure 6.

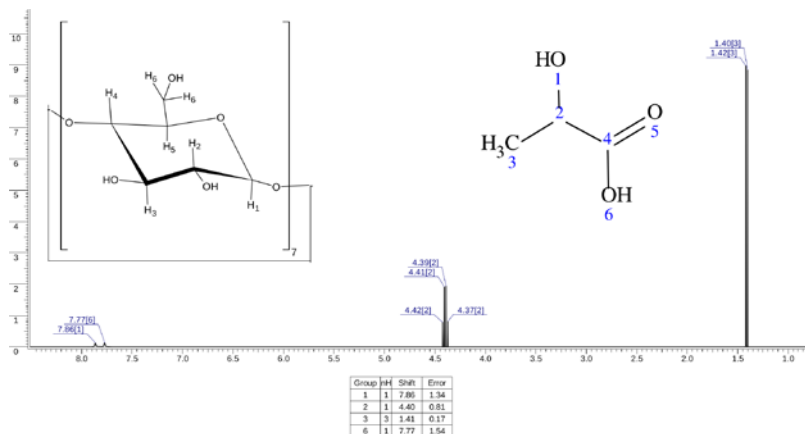


Figure 5 – ^1H NMR spectrum of SUPRADES in D_2O .

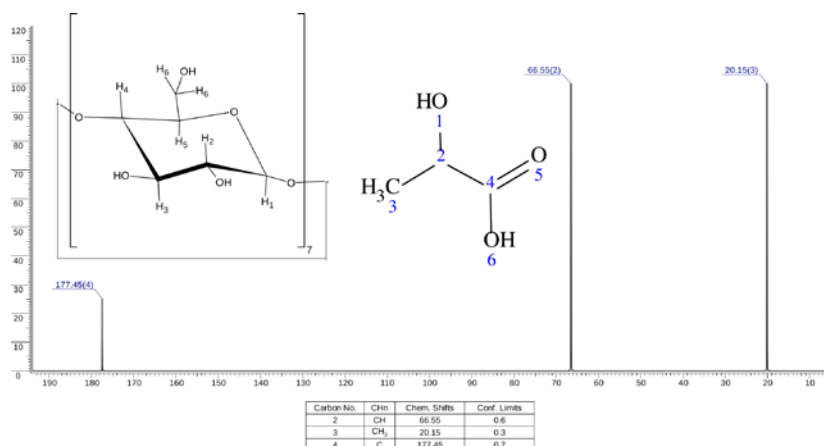


Figure 6 – ^{13}C NMR spectrum of SUPRADES in D_2O .

The structure of the compound was further examined by two-dimensional ^1H - ^1H COSY spectroscopy in D_2O . Characteristic homonuclear spin-spin correlations between neighboring lactic-acid protons were observed. Cross-peaks between the methyl (H-3) and methine (H-2) protons at 0.94/3.92 ppm and 3.92/0.94 ppm confirm their scalar coupling through three chemical bonds. One-bond ^1H - ^{13}C correlations were established by HMQC spectroscopy in D_2O . The COSY spectrum is shown in Figure 7.

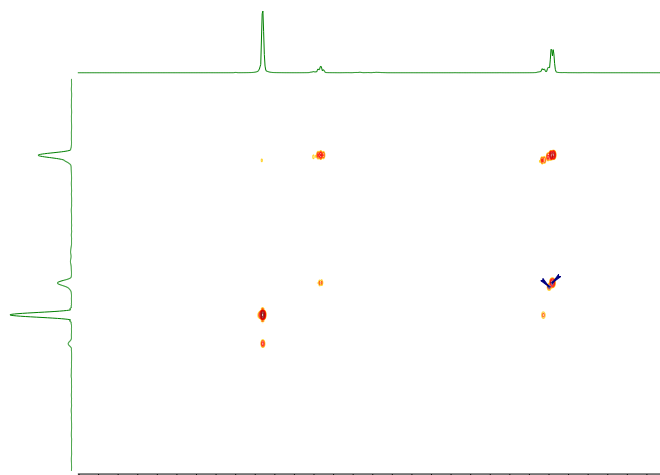


Figure 7 – COSY spectrum of SUPRADES in D₂O.

The following direct correlations were detected in the HMQC spectrum of SUPRADES: H-3/C-3 (0.95, 19.09 ppm) and H-2/C-2 (3.91, 66.06 ppm), confirming the lactic-acid fragment in the studied compound. Correlation signals of β -cyclodextrin were not detected because of its low concentration in the sample. Long-range heteronuclear correlations through two or more bonds were established by HMBC spectroscopy in D₂O. The H-3/C-2 (0.95, 66.61 ppm), H-3/C-4 (0.95, 178.16 ppm), H-2/C-3 (3.90, 19.18 ppm), and H-2/C-4 (3.90, 178.16 ppm) correlations support the constitutional connectivity of the lactic-acid fragment. The HMQC and HMBC spectra are presented in Figure 8.

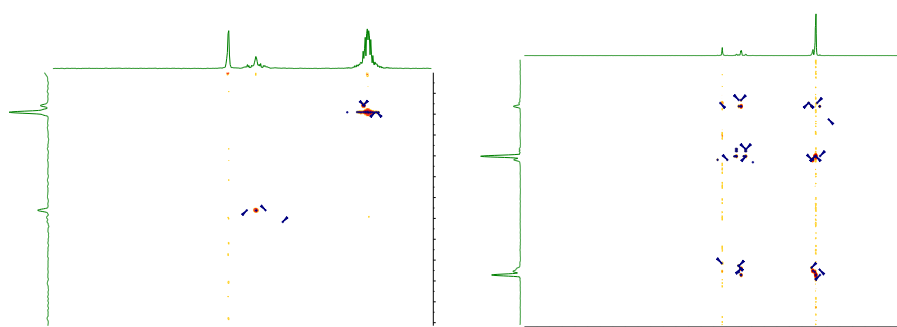


Figure 8 – (a) HMQC and (b) HMBC spectra of SUPRADES in D₂O.

4. Conclusion

This study evaluated β -cyclodextrin–lactic-acid SUPRADES as a potential modifier of asphaltene aggregation in a model oil prepared from Karazhanbas crude oil. FT-IR data were consistent with formation of a hydrogen-bonded

supramolecular network, TGA characterized the multistage thermal decomposition of the system, and ^1H , ^{13}C , COSY, HMQC, and HMBC NMR data confirmed the lactic-acid fragment and its principal correlations. In the representative UV–Vis spectra, absorbance near 292 nm decreased from approximately 0.88 to 0.59 after SUPRADES addition, corresponding to an apparent relative decrease of about 33%. Because the exact SUPRADES dose and mixing time linked to Figure 3 and replicate-level variability were not retained in the available record, this result is semiquantitative and should not be interpreted as a validated inhibition efficiency. Further work should use predefined SUPRADES concentrations, independent replicates, and complementary particle-size or precipitation measurements to establish dose–response behavior and quantitative inhibition performance.

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β-ЦИКЛОДЕКСТРИН МЕН СҮТ ҚЫШҚЫЛЫ НЕГІЗІНДЕГІ SUPRADES-тің АСФАЛЬТЕНДЕРДІҢ АГРЕГАЦИЯЛАНУ ПРОЦЕСТЕРІНЕ ӘСЕРІ

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Түйіндемe. *Kіріспе.* Асфальтендердің тұнуы мен агрегациялануы мұнайды өндіруді, тасымалдауды және өндеуді қиындатады. *Мақсаты.* β-Циклодекстрин мен L-сүт қышқылы негізіндегі SUPRADES жүйесінің Қаражанбас мұнайынан дайындалған модельдік мұнайдағы асфальтен агрегациясына әсерін бағалау. *Әдістері.* Асфальтендер ГОСТ 11858-66 бойынша бөлінді. SUPRADES 1:60 мольдік қатынаста алынып, FT-IR, УК–көрінетін спектроскопия, термогравиметрия және ^1H , ^{13}C , COSY, HMQC, HMBC ЯМР әдістерімен зерттелді. *Нәтижелері және талқылау.* FT-IR сутектік байланыстар желісін, TGA көпсатылы ыдырауды, ал ЯМР сүт қышқылы фрагменті мен негізгі корреляцияларды көрсетті. 292 нм маңында оптикалық тығыздық шамамен 0,88-ден 0,59-ға дейін төмендеді, яғни көрінетін төмендеу шамамен 33% болды. Қайталама өлшеулердің шашырауы болмағандықтан, нәтиже жартылай сандық деп түсіндірілді. *Қорытынды.* Жүйе асфальтен агрегациясын өзгертуі мүмкін, бірақ сандық тиімділік нақты концентрациялар мен тәуелсіз қайталамаларда расталуы тиіс.

Түйінді сөздер: β-циклодекстрин, сүт қышқылы, асфальтендер, агрегация, FT-IR-спектроскопия, УК–көрінетін спектроскопия, SUPRADES

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ВЛИЯНИЕ SUPRADES НА ОСНОВЕ β -ЦИКЛОДЕКСТРИНА И МОЛОЧНОЙ КИСЛОТЫ НА ПРОЦЕССЫ АГРЕГАЦИИ АСФАЛЬТЕНОВ

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Резюме. Введение. Осаждение и агрегация асфальтенов осложняют добычу, транспортировку и переработку нефти. Цель. Оценить влияние SUPRADES на основе β -циклодекстрина и L-молочной кислоты на агрегацию асфальтенов в модельной нефти, приготовленной из нефти Каражанбас. Методы. Асфальтены выделяли по ГОСТ 11858-66. SUPRADES получали при мольном соотношении 1:60 и исследовали методами FT-IR- и УФ-видимой спектроскопии, термогравиметрии и ¹H-, ¹³C-, COSY-, HMQC- и HMBC-ЯМР. Результаты и обсуждение. FT-IR указала на сеть водородных связей, TGA выявила многостадийное разложение, а ЯМР подтвердил фрагмент молочной кислоты и основные корреляции. При 292 нм оптическая плотность снизилась примерно с 0,88 до 0,59, то есть приблизительно на 33%. Из-за отсутствия данных о вариабельности повторных измерений результат интерпретирован как полуколичественный. Заключение. Система может изменять агрегацию асфальтенов, однако количественную эффективность необходимо подтвердить при заданных концентрациях и в независимых повторях.

Ключевые слова: β -циклодекстрин, молочная кислота, асфальтены, агрегация, FT-IR-спектроскопия, УФ-видимая спектроскопия, SUPRADES

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References

1. Ahmadi S., Khormali A., Kazemzadeh Y. A critical review of the phenomenon of inhibiting asphaltene precipitation in the petroleum industry. *Processes*, 2025, 13, No. 1, 212. DOI: 10.3390/pr13010212.
2. Zheng C., Brunner M., Li H., Zhang D., Atkin R. Dissolution and suspension of asphaltenes with ionic liquids. *Fuel*, 2019, 238, 129-138. DOI: 10.1016/j.fuel.2018.10.070
3. Kfoury M., Landy D., Fourmentin S. Combination of DES and macrocyclic host molecules: Review and perspectives. *Curr. Opin. Green Sustain. Chem.*, 2022, 36, 100630. DOI: 10.1016/j.cogsc.2022.100630
4. Cai Z.-H., Wang J.-D., Liu L., Ruan L.-D., Gu Q., Yan X.-Y., Fu L.-N., Zhao P.-Q., Zhang S., Fu Y.-J. A green and designable natural deep eutectic solvent-based supramolecular solvents system: Efficient extraction and enrichment for phytochemicals. *Chem. Eng. J.*, 2023, 457, 141333. DOI: 10.1016/j.cej.2023.141333.
5. Farooq M.Q., Zeger V.R., Anderson J.L. Comparing the extraction performance of cyclodextrin-containing supramolecular deep eutectic solvents versus conventional deep eutectic solvents by headspace single drop microextraction. *J. Chromatogr. A*, 2021, 1656, 462588. DOI: 10.1016/j.chroma.2021.462588
6. Christou A., Ioannou K.A., Ioannou G.D., Mavrou I., Stavrou I.J., Kapnissi-Christodoulou C.P. Supramolecular deep eutectic solvents as extraction media: A green approach for recovering carob pulp antioxidants. *J. Mol. Liq.*, 2026, 441, 129043. DOI: 10.1016/j.molliq.2025.129043.

7. Triolo A., Lo Celso F., Fourmentin S., Russina O. Liquid structure scenario of the archetypal supramolecular deep eutectic solvent: Heptakis(2,6-di-O-methyl)- β -cyclodextrin/levulinic acid. *ACS Sustain. Chem. Eng.*, 2023, 11, No. 24, 9103-9110. DOI: 10.1021/acssuschemeng.3c01858.
8. Balenzano G., Racaniello G.F., Lopedota A.A., Lopalco A., Arduino I., Laquintana V., Denora N. Cyclodextrin-based supramolecular deep eutectic solvent (CycloDES): A vehicle for the delivery of poorly soluble drugs. *Int. J. Pharm.*, 2023, 647, 123553. DOI: 10.1016/j.ijpharm.2023.123553.
9. Zhou P., Liu G., Fang H., Zhao Z., Zhang Y., Tang X., Li P., Zeng J., Deng Y., Zhang M. Supramolecular deep eutectic solvents: Current advances and critical evaluation of cyclodextrins from solute to solvent in emerging functional food. *Compr. Rev. Food Sci. Food Saf.* 2024. DOI: 10.1111/1541-4337.70026.
10. Sadek M., Sarkis N., Jangi G. A sustainable supramolecular deep eutectic solvent system for dispersive liquid-liquid microextraction followed by HPLC for the determination of melamine in milk samples. *Results Chem.*, 2026, 20, 103057. DOI: 10.1016/j.rechem.2026.103057.
11. Honarmandrad Z., Strzelczyk I., Kucharska K., Kaykhaii M., Słupek E., Gebicki J., Cydejko J. SUPRADES: A novel approach for inhibitor compound removal from hydrolysates with concurrent enhancement of biohydrogen production. *Int. J. Hydrogen Energy*, 2025, 135, 361-371. DOI: 10.1016/j.ijhydene.2025.04.351.
12. Hai X., Shi F., Zhu Y., Ma L., Wang L., Yin J., Li X., Yang Z., Yuan M., Xiong H., Gao Y. Development of magnetic dispersive micro-solid phase extraction of four phenolic compounds from food samples based on magnetic chitosan nanoparticles and a deep eutectic supramolecular solvent. *Food Chem.*, 2023, 410, 135338. DOI: 10.1016/j.foodchem.2022.135338.
13. Ioannou K.A., Stavrou J., Ioannou G.D., Christou A., Kapnissi-Christodoulou C.P., Schmid M.G. Novel supramolecular deep eutectic solvent (SUPRADES) as a sole chiral selector in capillary electrophoresis for the enantiomeric separation of fluorine-substituted amphetamine analogs. *J. Chromatogr. A*, 2024, 1715, 464628. DOI: 10.1016/j.chroma.2024.464628.
14. Gui C., Liu Q., Lei Z., Guo Y., Kfoury M., Xiang D., Fourmentin S. Supramolecular deep eutectic solvents and their aqueous solutions: Green carriers for essential oils. *ACS Sustain. Chem. Eng.*, 2025, 13, No. 18, 6611–6622. DOI: 10.1021/acssuschemeng.5c00881.
15. Hebbar A., Debraja D., Acharya S., Puttapati S.K., Vatti A.K., Dey P. Deep eutectic solvents interaction with asphaltenes: A combined experimental and molecular dynamics study. *J. Mol. Liq.* 2023, 390, 122627. DOI: 10.1016/j.molliq.2023.122627.