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The New Cationic Surfactant Based on Technical Vegetable Oil – A Residue of Sunflower Oil Production

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Abstract

A fatty acid mixture (FCA) was obtained from Technical Vegetable Oil – a Residue of Sunflower Oil production. Mass-spectrometry chromatogram analysis revealed that the mixture consists primarily of nine types of fatty acid. A new cationic surfactant (FCA-3-DMAPA surfactant) was obtained using the amidation reaction of a mixture of FCA with 3-dimethylamine-1-propylamine (3-DMAPA). The chemical structure of the synthesized surfactant was confirmed using mass-spectra chromatogram analysis, infrared, ^{1}H and ^{13}C nuclear magnetic resonance spectra. The surface-active and colloid-chemical properties of the synthesized surfactant (critical micelle concentration (CMC), wetting of teflon surface, emulsifiering, flocculating and biocidal properties) were studied. The maximal Gibbs adsorption at water/air interface (Γ_{max} = 4.8×10^{-6} mol/m^2), area occupied by one molecule of the cationic surfactant in the saturated adsorption layer (A_{min} = 0.35 nm^2), surface-activity (Π_{CMC} = 39.8 mN/m) and zeta-potential (ζ_{CMC} = +71 mV) at CMC were determined. It was established that the obtained cationic surfactant has good wetting, emulsifying, flocculating and biocidal properties.

Keywords: Surfactant; Renewable raw material; Wetting agent; Emulsifier; Biocide.

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1. Introduction

The increasing interest in sustainable development and environmentally benign technologies has stimulated an active search for alternatives to conventional chemical products derived from non-renewable feedstocks.[1,2] Particular attention has been directed toward surface-active substances (surfactants), which are extensively employed in diverse sectors including household chemistry, cosmetics, agriculture, and petrochemistry.[3-6] Among them, cationic surfactants occupy a distinctive position due to their pronounced antibacterial, conditioning, and adsorption properties.[7,8] Within this class, the most common hydrophilic head group is the quaternary ammonium ion, in which the nitrogen atom is covalently bonded to four alkyl or aryl substituents.

Traditionally, cationic surfactants are synthesized from petrochemical raw materials, a process associated with several significant drawbacks. These include the high energy demand of industrial operations, the generation of compounds with considerable toxicity and limited biodegradability, the release of substantial amounts of greenhouse gases, and persistent reliance on non-renewable resources.[9,10] Such factors underscore the necessity of developing new synthetic approaches to surfactants based on renewable raw materials. The utilization of renewable feedstocks such as vegetable oils, sugars, carbohydrates, amino acids, and other biogenic compounds offers promising opportunities for the design of environmentally safer, biodegradable, and resource-efficient products that can reduce the ecological footprint and align with the concept of "Green Surfactants.[11,12] The development of such compounds not only meets increasingly stringent environmental regulations but also contributes to the emergence of new markets for eco-friendly materials.

At present, there are two main approaches to obtaining "green surfactants": the synthesis of surfactants using bacteria (biosurfactants) and from plant oils and animal fats (oleo-surfactants).[12] Biosurfactants derived from natural resources

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are not only difficult to produce on an industrial scale, but their production is relatively slow, labor-intensive, and costly. Therefore, the production of biodegradable surfactants from renewable raw materials of plant and animal origin (oleo-surfactants) is considered one of the most promising directions.

The prospects of obtaining various surfactants (anionic, cationic, non-ionic, and zwitterionic) from cashew nut shell liquid (CNSL) were discussed. CNSL is an oil obtained from the inedible shell of cashew nuts.[12]

Cardanol (3-pentadecylphenol), considered "a promising renewable natural resource,[13] is isolated from CNSL by vacuum distillation. In this case, the hydrophobic tail may be saturated, mono-olefinic, di-olefinic, or tri-olefinic.[12] Various cationic surfactants have been obtained through the alkylation, amination, or quaternization of cardanol. Cardanol (CNSL)-based surfactants generally exhibit higher biodegradability compared to surfactants obtained from petroleum-derived products and are widely used in emulsion polymerization,[14-16] the polymer industry, paints and coatings, adhesives, emulsifiers, corrosion inhibitors, wetting agents, enhanced oil recovery, and the textile industry.[12,13]

Several types of cationic surfactants based on renewable raw materials were obtained using environmentally friendly methods (without solvents and pollutants).[17] In these cases, sugars or betaine were employed as the polar head groups of the surfactants, while natural oils served as the lipophilic part. The reactions were carried out in the presence of an excess reagent, which was subsequently recycled. For example, esterification reactions of glycine betaine were conducted with saturated or unsaturated fatty alcohols of various chain lengths (lauryl, stearyl, or oleyl alcohols) at 130 °C, in the presence of biodegradable methanesulfonic acid and under low pressure. The resulting surfactants demonstrated high foaming and emulsifying capacities, making them applicable in the detergent, cosmetic, and oil recovery industries.

Existing methods for obtaining cationic carbohydrate-based surfactants were described in several articles.[18-21] In this case, cationic surfactants are mainly synthesized by attaching various amines (primary, secondary, tertiary) to the hydrophilic groups of carbohydrates.[22,23] The incorporation of a glucose moiety imparts bacteriostatic properties, enhances molecular aggregation, and also improves the biodegradability of the surfactant. Consequently, cationic carbohydrate-based surfactants exhibit relatively low critical micelle concentrations (CMC) and significantly reduce surface free energy.[24]

20 types of cationic surfactants were obtained.[25] For the synthesis of alkyl halides, four fatty acids (lauric, palm, myristic, and oleic acids) were used as raw materials. For this purpose, the fatty acids were first reduced to fatty alcohols, which were then converted into the corresponding alkyl fatty halides by reaction with hydrobromic acid. Subsequently, aliphatic and aromatic amines were ethoxylated to obtain unconventional tertiary amines. The quaternary ammonium salt-based surfactants (QASs) were prepared by refluxing the alkyl halide with the tertiary amine. Then the resulting cationic surfactants were tested as corrosion inhibitors for carbon steel in 1 M HCl solution. It was established that the inhibitory efficiency of QASs based on ethoxylated aromatic tertiary amines was higher than that of QASs derived from ethoxylated aliphatic tertiary amines.

Thus, the literature review has shown that there is no information available regarding the use of technical vegetable oil - a by-product of sunflower oil production, as a raw material for the synthesis of cationic surfactants. Technical vegetable oil is an accessible renewable feedstock, and its application for surfactant synthesis opens up broad prospects for the production of more environmentally safe, biodegradable cationic surfactants.

The objective of this study is the synthesis of a cationic surfactant from technical vegetable oil - a by-product of sunflower oil production.

2. Experimental

2.1 Materials

Technical vegetable oil – a residue of sunflower oil production – was used as a hydrophobic fragment for the synthesis of cationic surfactant. A mixture of fatty carboxylic acids (FCA) was isolated from the technical vegetable oil using methods of alkaline hydrolysis, acid treatment, and extraction. The procedure for isolating the FCA mixture was described in detail.[26]

Concentrated solutions of sodium hydroxide and sulfuric acid (purity ≥ 95 wt %) were used for the hydrolysis of fatty acid esters.

3-dimethylamine-1-propylamine (3-DMAPA) (Sigma Aldrich, purity ≥ 98 %) was used as the hydrophilic fragment for the synthesis of cationic surfactant.

To investigate the flocculating properties of the surfactant, a kaolin suspension was used. According to the results of spectroscopic analysis, the main composition (99.71 %) of kaolin consists of SiO_2 (58.8 %), Al_2O_3 (38.9 %), Fe_2O_3 (1.04 %), TiO_2 (0.52 %), and K_2O (0.45 %).

2.2 Methods

Infrared (IR) spectra of the synthesized surfactant and other related compounds were obtained using a BRUKER ALPHA FTIR spectrometer.

^1H and ^{13}C Nuclear Magnetic Resonance (NMR) spectra were recorded on a JNM-ECA Jeol 400 spectrometer (operating frequencies 399.78 and 100.53 MHz, respectively) using $CDCl_3$ as the solvent. Chemical shifts were measured relative to the signals of residual protons or carbon atoms of deuterated chloroform Gas chromatography–mass spectrometry (GC–MS) analysis of the mixture was performed using an Agilent 7890B gas chromatograph equipped with an Agilent 5977B quadrupole mass-selective detector (ionization energy: 70 eV; ion source temperature: 230 °C; quadrupole temperature: 150 °C), following the procedure described.[27,28] Separation was carried out on a HP-5ms UI capillary column

(30 m × 0.25 mm i.d., 0.25 μm film thickness; Agilent, USA). Helium was used as the carrier gas at a flow rate of 1 mL/min. Sample introduction was performed in split mode (1:20). The oven temperature program was as follows: isothermal at 80 °C for 2 minutes, then ramped to 280 °C at a rate of 5 °C/min. The injector temperature was set at 280 °C; injection volume was 1 μL. The detector interface temperature was maintained at 280 °C. The mass scan range was 30–550 m/z.

The software used for processing the chromatographic–mass spectrometric data included MassHunter Qualitative Analysis (Version B.06.00, Agilent Technologies), NIST MS Search 2.0, and the NIST11 mass spectral library (release date: May 19, 2011).[27]

The surface tension (σ) of aqueous surfactant's solutions at the air/water interface was measured at room temperature using the Wilhelmy plate method with a SZFL-A1 tensiometer (model A1 series).[29] The measurement accuracy was 0.1 mN/m. In this method, a platinum plate is gradually lowered into a surfactant solution until it comes into contact with the surface. After contact, the force required to detach the plate from the surface is measured. Based on the measured detachment force, surface tension is calculated using the following Eq. (1):

$$\sigma = F/(L \cdot \cos\theta) \quad (1)$$

where σ is the surface tension of the solution (mN/m), F is the detachment force (mN), L is the perimeter of the wetted part of the plate (L = 2·*l*, where *l* is the width of the lower edge of the plate), in meters.

Due to the roughness of the platinum plate surface, complete wetting occurs (θ = 0), and therefore cos θ = 1. Surface tension for each solution was measured five times, and the arithmetic mean value of σ was reported.

To evaluate the surface activity of the synthesized surfactants, the following parameters were determined:

1. Surface pressure at the critical micelle concentration (Π_{CMC}) was calculated as the difference between the surface tension of water (σ_0) and that of the surfactant solution at the CMC (σ_{CMC}) using the following Eq. (2):[30, 31]

$$\prod_{CMC} = \sigma_0 - \sigma_{CMC} \quad (2)$$

2. Maximum surface excess concentration (Γ_{max}) at the air/water interface was determined from the surface tension isotherm σ = f(ln C), using the Gibbs adsorption Eq. (3):[32-34]

$$\Gamma_{max} = -a/R \times T \times n \quad (3)$$

where *a* is the slope of the linear portion of the σ vs. ln C plot below the CMC (i.e., *a* = (dσ/lnC), *R* is the universal gas constant (8.314 J/(mol×K)), T is the absolute temperature (K) and *n* is the number of species adsorbed at the interface. For nonionic surfactants, *n* = 1.

3. Minimum area per molecule (A_{min}) in the saturated adsorption layer was calculated according to the following Eq. (4):[33,34]

$$A_{min} = 10^{18}/N_A \times \Gamma_{max} \quad (4)$$

where N_a is Avogadro's number (6.022×10^{23} mol^{-1}).

4. pC_{20}, an empirical parameter characterizing the efficiency of surface tension reduction, was calculated using the following Eq. (5):[35]

$$pC_{20} = -\log(C_{20}) \quad (5)$$

where C_{20} is the surfactant concentration at which the surface tension of water is reduced by 20 mN/m.

The acid number of the oil (X, mg KOH/g) was calculated using the following Eq. (6):[36,37]

$$X = (5.611 \times V)/m \quad (6)$$

where 5.611 is the mass of KOH in 1 cm^3 of a solution with a molar concentration of c(KOH)=0.1 mol/dm^3, mg, V is the volume of a KOH solution with a molar concentration of c(KOH) = 0.1 mol/dm^3, spent on titration, cm^3 and m is the mass of the sample, g.

The influence of surfactants on the stability of an emulsion of industrial oil (I-20A) in water was evaluated in accordance with the procedure outlined.[38] Equal volumes (25 mL each) of surfactant solution (at a given concentration) and industrial oil were mixed in a graduated cylinder. Then the mixture was subjected to ultrasonic dispersion using a probe-type ultrasonic disintegrator (Scientz JY92-IIDN, Horn 2, program 1, power 50%, T-on 2.0 s, T-off 2.0 s.) for 3-5 minutes at room temperature.

After sonication, phase separation of the emulsion was monitored at 1, 24, 48, and 72 hours under ambient conditions. Emulsion stability (Z) was assessed by measuring the volume of oil separated from the emulsion according to the following Eq. (7):

$$Z = (V_0 - V_\tau) \times 100\%/V_0 \quad (7)$$

where V_0 is the total volume of oil (25 mL) added to the aqueous surfactant solution, and V_τ is the volume of oil separated from the emulsion at time τ. Ultrasonic dispersion was used to generate fine and more stable emulsions compared to conventional mechanical stirring.

The coagulating properties of the synthesized surfactant were studied in a suspension of kaolin.

At the initial stage of the experiment, kaolin was ground in a mill at a speed of 300 rpm for 10 minutes, and the resulting powder was then passed through a sieve with a mesh size of 0.1 mm. After that, 0.3 g of the powder was placed in a graduated cylinder, 99.7 mL of bidistilled water was added (0.3 wt. %), and the suspension was left in a closed container for 24 hours to allow swelling. Before use, the suspension was mixed in a mixer for 3 minutes at a speed of 100 rpm. Then, 10 mL of the suspension was transferred into several test tubes, and the required amounts of surfactant solution were added under vigorous stirring.

Coagulation of kaolin particles in the presence of surfactant was studied by measuring the optical density (OD)

of the suspension. OD was measured using an i3 Ultraviolet-visible (UV-VIS) spectrometer (China) at a wavelength of incident light of 546 nm. Bidistilled water was used as the standard. The residual turbidity (RT, %) was calculated according to the following Eq. (8):[39,40]

$$RT = (OD_{546s}/OD_{546i}) \times 100\% \quad (8)$$

where OD_{546s} denotes OD_{546} after the addition of the coagulant and OD_{546i} denotes OD_{546} of the suspension in the absence of coagulant under the same experimental conditions.

The electrokinetic (zeta) potential (ζ) of surfactant's colloidal particles in aqueous solutions at the CMC concentration, as well as that of the kaolin and teflon suspensions in water, was determined at room temperature using a Zetasizer Advance Series ZSU3200-Pro (Blue Label) manufactured by Malvern Panalytical. The value of the zeta potential was calculated using software based on the Helmholtz–Smoluchowski equation. The measurement error did not exceed 1%. The average value was obtained from three measurements.

The effect of the cationic surfactant on the water contact angle (θ) of a solid surface was investigated using a Teflon plate. The contact angle was measured with a DSA10 instrument (Kruss). The Teflon plate was first washed with soapy water, then treated in a hot chromic acid mixture for 10–15 minutes. After cleaning, the plate was rinsed several times with bidistilled water and air-dried.

The cleanliness of the Teflon surface was verified by measuring the contact angle of bidistilled water. For Teflon, the water contact angle was 101°. The contact angle was measured 15–20 seconds after the droplet was applied to the solid surface. From each solution, five droplets were applied to the solid surface, and the contact angle was measured from two sides. The arithmetic mean of the contact angle was calculated from five measurements. The measurement error of the contact angle did not exceed 1°.

The biocidal properties of the cationic surfactant FCA-3-DMAPA against sulfate-reducing bacteria (SRB) were studied at the Laboratory of Environmental and Agricultural Microbiology, Scientific and Production Center of Microbiology and Virology LLP (Almaty, Kazakhstan). The effect of the cationic surfactant on the development of SRB was studied within a concentration range of 0.01–1.0 %.

The biocidal properties of the cationic surfactant FCA-3-DMAPA against the enrichment culture of SRB were determined as follows: 1 mL of the enrichment culture of SRB was added to experimental test tubes, which were then filled with Postgate medium containing the cationic surfactant at the corresponding concentration and sealed with rubber stoppers to create anaerobic conditions. In the control variant (C), SRB were cultured without surfactant. The test tubes were incubated in a thermostat for 15 days at 30 °C. All surfactant solutions and suspensions were prepared in bidistilled water.

3. Results and discussion

3.1 Analysis of the chromatography

In order to determine the composition of the mixture obtained after the hydrolysis of technical vegetable oil and the extraction of fatty carboxylic acids, a chromatography–mass spectrometry analysis of the mixture was conducted. For this purpose, the fatty carboxylic acids in the mixture were preliminarily converted into methyl esters by means of an esterification reaction.[27,28] The results of the chromatography–mass spectrometry analysis are presented in Fig. 1, Tables 1 and 2.

According to the fragmentation mechanism of fatty carboxylic acids (FCA) resulting from electron ionization (EI) of the analyzed compounds, base peaks characteristic of the studied fatty acids were identified.[27,28] The identification of components in the reaction mixture, represented as peaks on the chromatogram, was carried out based on the analysis of the mass spectra of each compound. Through detailed examination of the mass spectra and according to the fragmentation mechanism under electron ionization, the composition of the methyl esters of FCA was determined and presented in Table 2.

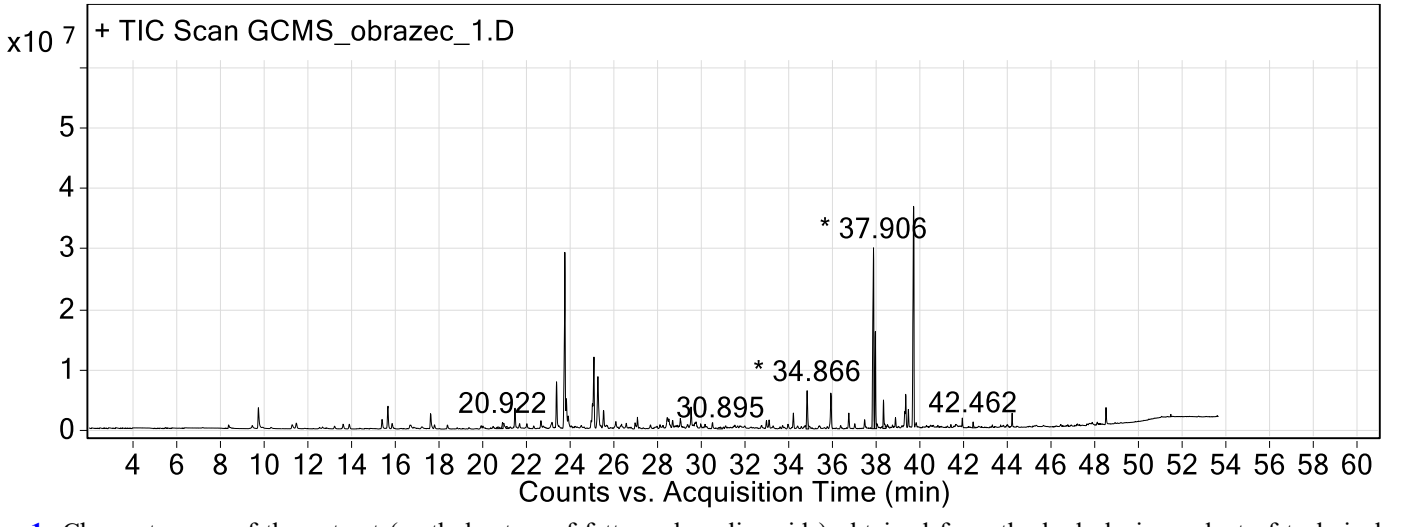


Fig. 1: Chromatogram of the extract (methyl esters of fatty carboxylic acids) obtained from the hydrolysis product of technical vegetable oil.

Table 1: User chromatogram peak list.

RT	Height	Height %	Area	Area %	Area sum %	Symmetry	Width
20.741	277218.32	0.93	2447951.6	2.49	1.34	1	0.25
20.922	1000995.5	3.35	3100876.84	3.16	1.7	0.63	0.095
21.12	348225.12	1.16	1918437.48	1.95	1.05	2.33	0.146
30.895	318313.78	1.06	2614859.57	2.66	1.43	0.6	0.258
34.866	6338783.5	21.18	20394066.08	20.75	11.18	1.4	0,129
37.906	29921448.68	100	98282399.33	100	53.88	0.46	0.129
37.992	16050644.47	53.64	37760134.75	38.42	20.7	0.77	0.103
38.363	4725054.69	15.79	13149403.69	13.38	7.21	3.02	0.155
42.462	978826.63	3.27	2741811.75	2.79	1.5	3.6	0.189

Table 2: Content of methyl esters of fatty carboxylic acids.

Compound label	RT	Name	Area sum, %
Cpd 1: 2-Decenoic acid, methyl ester	20.741	2-Decenoic acid, methyl ester	1.34
Cpd 2: 4-Decenoic acid, methyl ester	20.922	4-Decenoic acid, methyl ester	1.7
Cpd 3: Decanoic acid, methyl ester	21.12	Decanoic acid, methyl ester	1.05
Cpd 4: Oxiraneundeca-noic acid, 3-pentyl-, methyl ester, cis-	30.895	Oxiraneundecanoic acid, 3-pentyl-, methyl ester, cis-	1.43
Cpd 5: Hexadecanoic acid, methyl ester	34.866	Hexadecanoic acid, methyl ester	11.18
Cpd 6: 9,12-Octadeca-dienoic acid (Z,Z)-, methyl ester	37.906	9,12-Octa-decadie-noic acid (Z,Z)-, methyl ester	53.88
Cpd 7: 9-Octadecenoic acid (Z)-, methyl ester	37.992	9-Octadecenoic acid (Z)-, methyl ester	20.7
Cpd 8: Methyl stearate	38.363	Methyl stearate	7.21
Cpd 9: Docosanoic acid, methyl ester	42.462	Docosanoic acid, methyl ester	1.5

The results of the chromatography–mass spectrometry analysis are expressed as the percentage content of individual methyl esters of fatty acids. The analysis was performed using a flame ionization detector (FID), which allows the peak areas to be interpreted as relative mass fractions.

As shown in Table 2, the mixture of fatty carboxylic acids consists of 9 types of saturated and unsaturated acids, with the highest mass fractions corresponding to 9, 12-octadecadienoic acid (linoleic acid) and 9-octadecenoic acid (oleic acid). In addition to fatty carboxylic acids, other cycloaliphatic and unsaturated cyclic organic compounds were also detected, including: 2, 6, 6-trimethylbicyclo [3.1.1] hept-2-ene, bicyclo [3.1.0] hexane, 4-methylene-1-(1-methylethyl)-, and 2-(1R,4R)-4-hydroxy-4-methylcyclohex-2-enyl) propan-2-yl acetate.

3.2 Synthesis of cationic surfactant based on FCA and 3-DMAPA

For the synthesis of the cationic surfactant, 3-DMAPA and a mixture of FCA isolated from technical vegetable oil were used in a molar ratio of 1:1. In a three-necked flask equipped with a reflux condenser, thermometer, Dean–Stark trap, and overhead stirrer, 40 g of 3-DMAPA and 19 mL of the FCA mixture were placed. Then the mixture was heated to 160–165 °C and maintained at this temperature for 4 hours with the collection of the released water in the Dean–Stark trap. The amidation reaction was monitored by determining the acid number (Fig. 2).[36]

The reaction was continued until the acid number of the mixture reached a constant value. The amount of amides formed during the reaction (reaction yield) was calculated based on the volume of water collected in the Dean–Stark trap

and the acid number of the mixture (Fig. 2). The obtained amide of FCA with 3-DMAPA was then cooled to room temperature. The amino group of the surfactant was converted into the salt form by adding concentrated hydrochloric acid at room temperature in an equimolar ratio for 1 hour. The reaction yield was 85.7 %. The synthesized cationic surfactant has the following proposed structural formula (R is the hydrocarbon radical of the carboxylic acid) (Fig. 3).

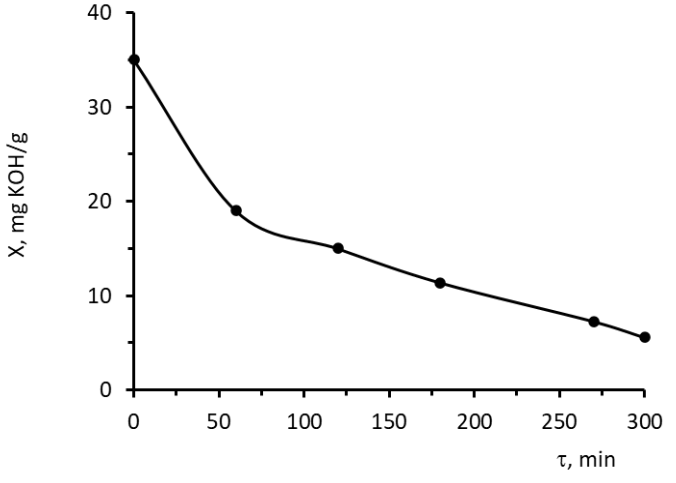


Fig. 2: Change in the acid number of the mixture during the reaction of FCA with 3-DMAPA.

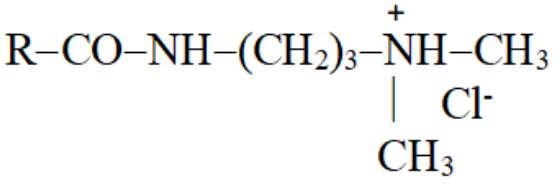


Fig. 3: Structural formula of the FCA-3-DMAPA surfactant.

3.3 Determination of the composition of cationic surfactant FCA-3-DMAPA

The chromatographic–mass spectrometric analysis of the mixture was carried out on an Agilent 7890B gas chromatograph equipped with an Agilent 5977B quadrupole mass-selective detector, with an ionization energy of 70 eV (ion source temperature 230 °C, mass filter temperature 150 °C).

Using the gas chromatography–mass spectrometry (GC/MS) method, a mixture of N,N-dimethylaminopropylamides of fatty acids was analyzed. According to the fragmentation mechanism of dimethylaminopropylamides of fatty acids arising from EI, the base peaks characteristic of the studied propylamide derivatives were identified. These results are presented in Fig. 4 and Table 3.

The identification of components in the reaction mixture, represented as peaks on the chromatogram, was carried out based on the analysis of their mass spectra.[27,28] Through a detailed examination of the mass spectra of these compounds according to the fragmentation mechanism under electron ionization, the following composition of FCA-3-DMAPA amides was determined, as presented in Table 3.

In the mixture, along with FCA amides, other cycloaliphatic compounds were also detected. The obtained cationic surfactant is a dark brown liquid that dissolves well in water.

3.4 Analysis of the IR spectrum of the cationic surfactant FCA-3-DMAPA

In the IR spectrum (Fig. 5), at a frequency of 1645 cm^{-1}, stretching vibrations of the C=O group (Amide I band) are observed.[41-43] The secondary Amide II band (composite frequencies of NH bending vibrations and C–N stretching) appears at 1548 cm^{-1}. Absorption bands characteristic of $–CH_2–$ groups are detected at frequencies of 2852–2922 cm^{-1}. At 1377 cm^{-1}, an absorption band typical for the $–CH_2–CO–$ group is observed. At 3330 cm^{-1}, stretching vibrations of the N–H group of the secondary amide are present. Therefore, based on the IR spectrum, it can be concluded that the obtained compound is a cationic surfactant based on FCA and 3-DMAPA.

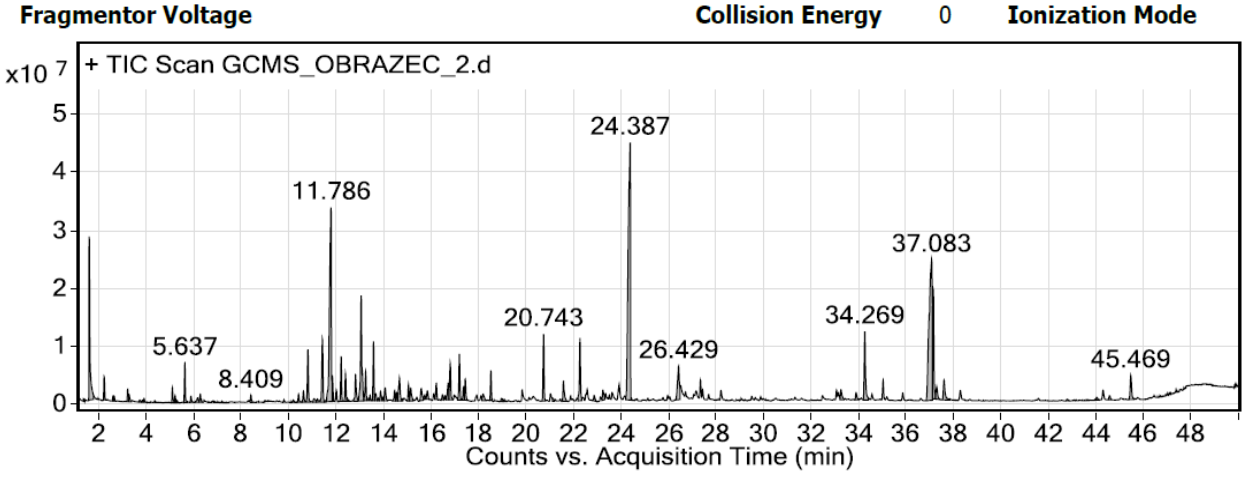


Fig. 4: Chromatogram of the total ion current (fragment) of the cationic surfactant based on FCA and 3-DMAPA.

Table 3: – Qualitative compound report of the cationic surfactant based FCA and 3-DMAPA.

Compound label	RT	Name	Area sum, %
Cpd 72: Kaur-16-ene	24.387	Kaur-16-ene	18.06
Cpd 73: 10E,12Z- Octadecadie-noic acid	26.429	10E,12Z-Octadecadienoic acid	1.96
Cpd 74: N-(3-(dimethylamino)-propyl)dodecanamide	33.266	N-(3-(dimethylamino)pro-pyl)dodecanamide	0.49
Cpd 75: N-(3-(dimethylamino)-propyl)tetradecanamide	33.901	N-(3- (dimethylamino)pro-pyl)tetradecanamide	0.32
Cpd 76: N-(3- (dimethylamino)-propyl)palmitamide	34.269	N-(3- (dimethylamino)pro-pyl)palmitamide	2.78
Cpd 77: (9Z,12Z)-N-(3-(di-methylamino)propyl)octadeca -9,12-dienamide	37.083	(9Z,12Z)-N-(3- (dimethyl-amino)propyl)octadeca-9,12-dienamide	13.73
Cpd 78: N-(3- (dimethylamino)-propyl)oleamide	37.154	N-(3-(dimethylamino)pro-pyl)oleamide	4.36
Cpd 79: Supraene	37.296	Supraene	0.64
Cpd 80: N-(3- (dimethylamino)-propyl)stearamide	37.605	N-(3- (dimethylamino)pro-pyl)stearamide	1.09
Cpd 81: Vitamin E	42.787	Vitamin E	0.07
Cpd 82: Campesterol	44.033	Campesterol	0.14
Cpd 83: Stigmasterol	44.573	Stigmasterol	0.19
Cpd 84: Gamma.-Sitosterol	45.469	Gamma.-Sitosterol	1.12

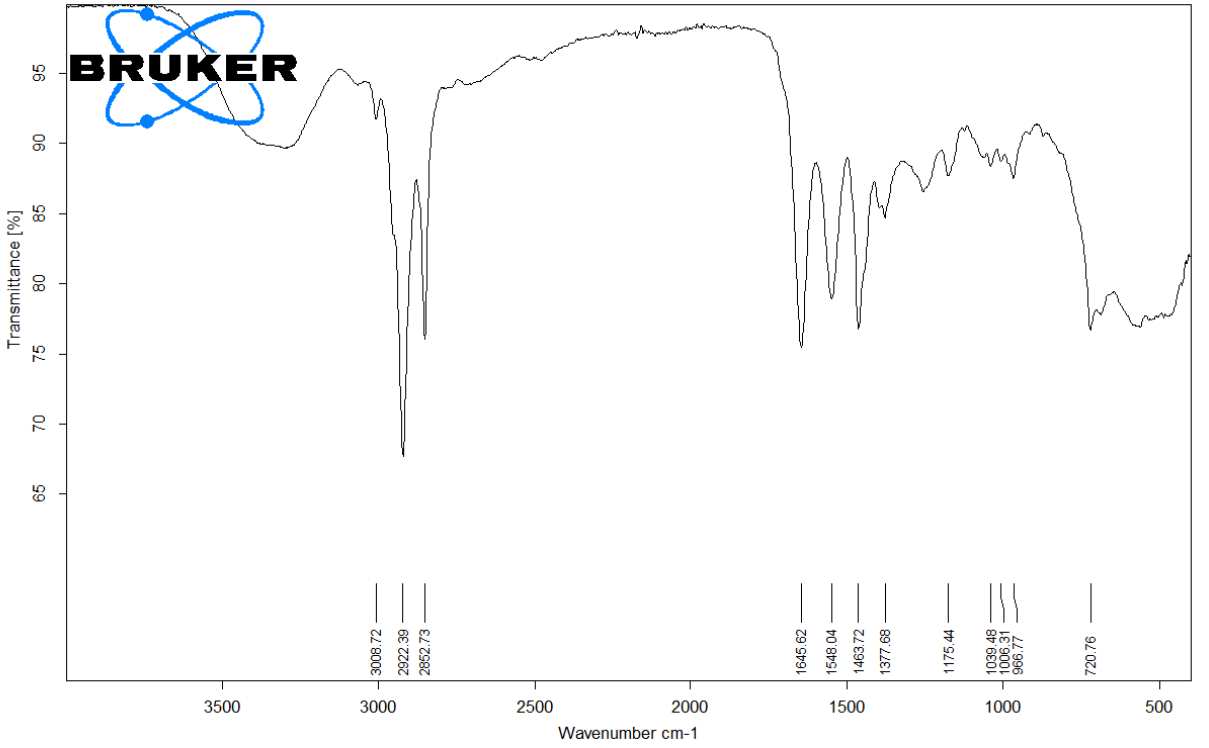
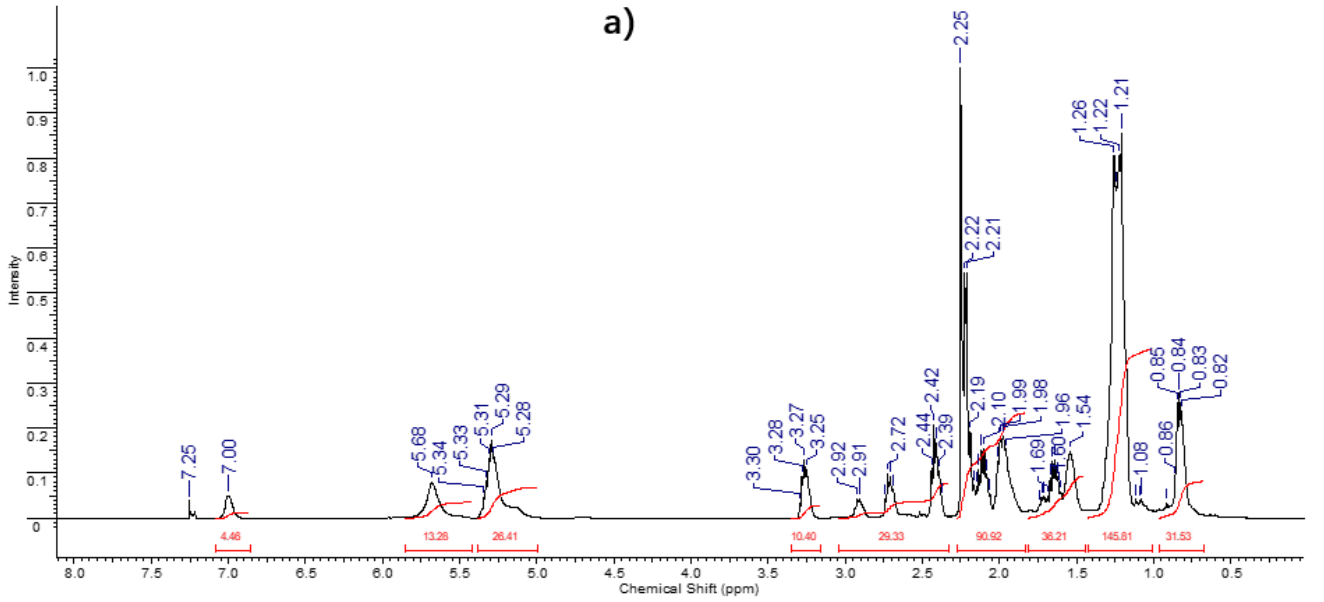


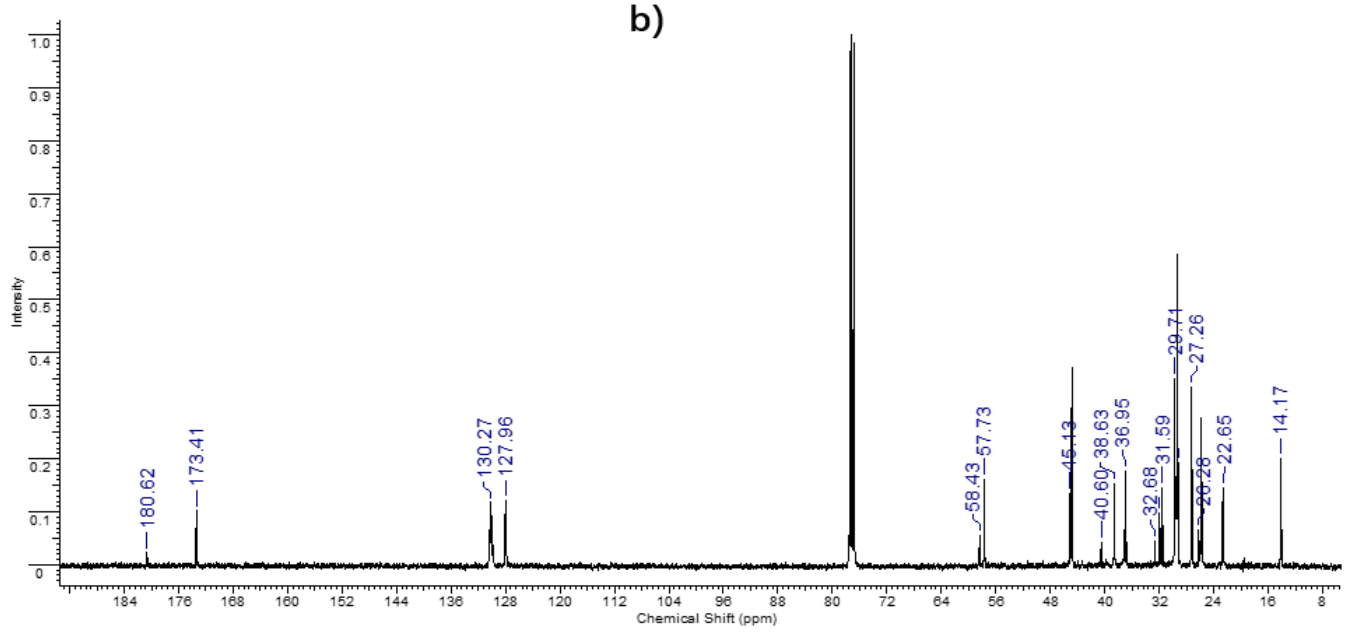
Fig. 5: IR spectrum of the cationic surfactant based on FCA and 3-DMAPA.

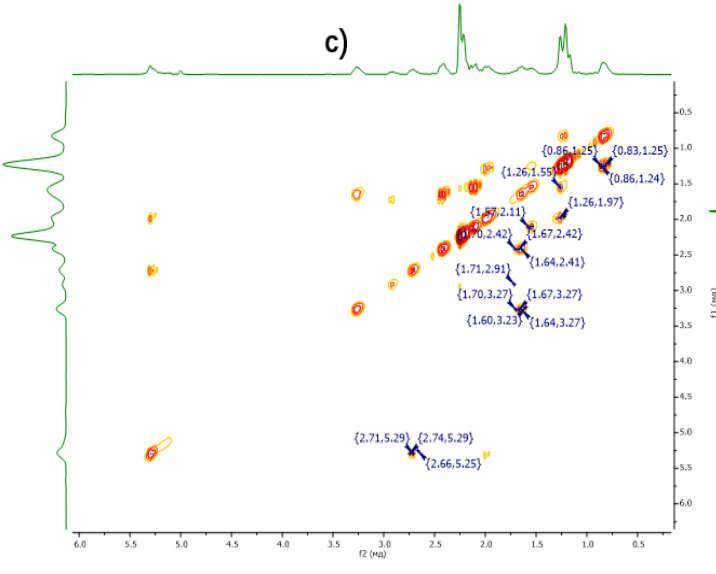
3.5 Analysis of NMR spectra of the cationic surfactant FCA-3-DMAPA

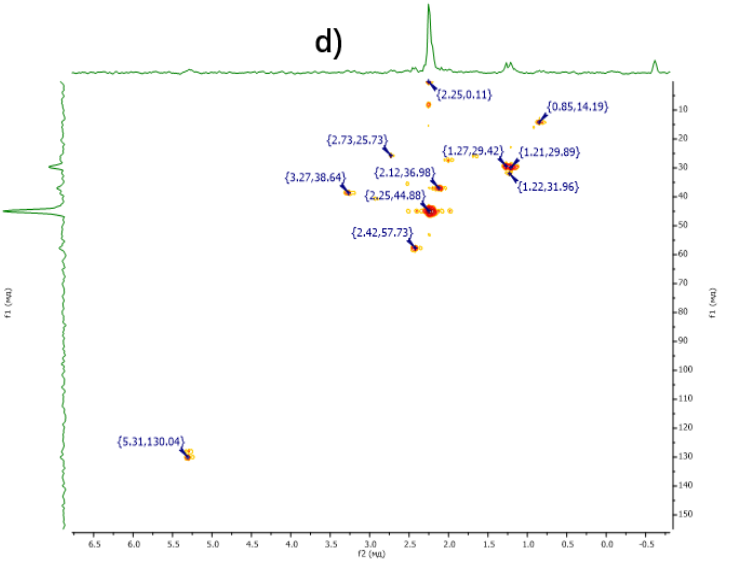
The ^{1}H NMR spectrum of FCA amides with 3-DMAPA in hydrochloric acid solution (Fig. 6a) is characterized by the presence of signals from protons of various fragmentary structures throughout the entire spectral range. In the region of 0.60–3.30 ppm, signals of protons from methyl and methylene groups of FCA residues and 3-DMAPA fragments are observed. This is one of the most abundant groups of fragments in the mixture of FCA–3-DMAPA amides.

The integral proton intensity of these signals amounts to 302.80H. Signals in the region of 5.00–5.68 ppm correspond to protons adjacent to oxygen atoms or other electronegative functional groups, as well as to protons belonging to


a)
Intensity
Chemical Shift (ppm)
7.25
7.00
5.68
5.34
5.33
5.31
5.29
5.28
3.30
3.28
3.27
3.25
2.92
2.91
2.72
2.44
2.42
2.39
2.25
2.22
2.21
2.19
2.10
1.99
1.98
1.96
1.69
1.60
1.54
1.26
1.22
1.21
1.08
0.86
0.85
0.84
0.83
0.82
4.46
13.26
26.41
10.40
29.33
90.92
36.21
145.81
31.53


b)
Intensity
Chemical Shift (ppm)
180.62
173.41
130.27
127.96
58.43
57.73
45.13
40.60
38.63
36.95
32.68
31.59
29.71
27.26
20.28
22.65
14.17


c)
{0.86,1.25}
{0.83,1.25}
{1.26,1.55}
{0.86,1.24}
{1.26,1.97}
{1.67,2.11}
{1.70,2.42}
{1.67,2.42}
{1.64,2.41}
{1.71,2.91}
{1.70,3.27}
{1.67,3.27}
{1.60,3.23}
{1.64,3.27}
{2.71,5.29}
{2.74,5.29}
{2.66,5.25}


d)
{2.25,0.11}
{0.85,14.19}
{2.73,25.73}
{1.27,29.42}
{1.21,29.89}
{3.27,38.64}
{2.12,36.98}
{1.22,31.96}
{2.25,44.88}
{2.42,57.73}
{5.31,130.04}

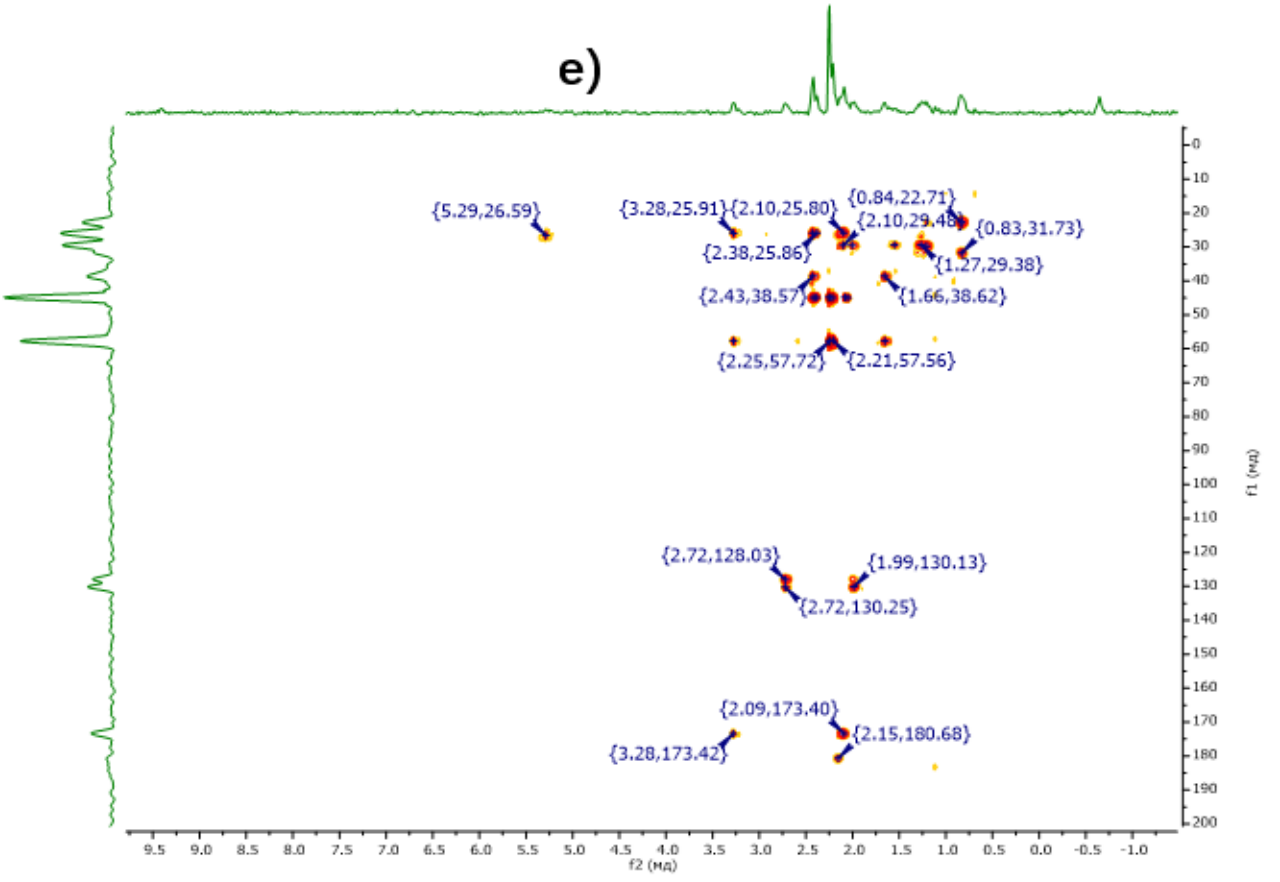


Fig. 6: NMR-spectra of the cationic surfactant based on FCA and 3-DMAPA. a) ^{1}H NMR in $CDCl_3$; b) ^{13}C NMR in $CDCl_3$; c) COSY (^{1}H-^{1}H) in $CDCl_3$; d) HMQC (^{1}H-^{13}C) in $CDCl_3$; e) HMBC (^{1}H-^{13}C) in $CDCl_3$.

unsaturated fragments of carboxylic acids.[43]

In the ^{13}C NMR spectrum of FCA–3-DMAPA amides (Fig. 6b), signals of carbon atoms of methyl and methylene groups appear in the range of 14.17–40.60 ppm.

The structure of FCA amides with 3-DMAPA was also confirmed by two-dimensional NMR spectroscopy methods COSY (^{1}H–^{1}H), HMQC (^{1}H–^{13}C), and HMBC (^{1}H–^{13}C) (Figs. 6c–6e), which allow the determination of spin–spin interactions of both homo- and heteronuclear nature. The observed correlations in COSY (^{1}H–^{1}H), HMQC (^{1}H–^{13}C), and HMBC (^{1}H–^{13}C) spectra of FCA–3-DMAPA amides confirm the above-mentioned assumptions.

3.6 Surface activity of the cationic surfactant FCA-3-DMAPA at the water/air interface

To determine the surface activity, the surface tension of aqueous solutions of the synthesized cationic surfactant was measured, and surface tension isotherms of the solutions were plotted (Fig. 7).

From the surface tension isotherms, the critical micelle concentration (CMC), surface tension at the CMC (σ_{CMC}) and other adsorption parameters were determined. The calculation results are presented in Tables 4 and 5. From these results, it follows that the ability of FCA-3-DMAPA surfactant to reduce the surface tension (σ) of water is greater than that of FCA-Na (soap).

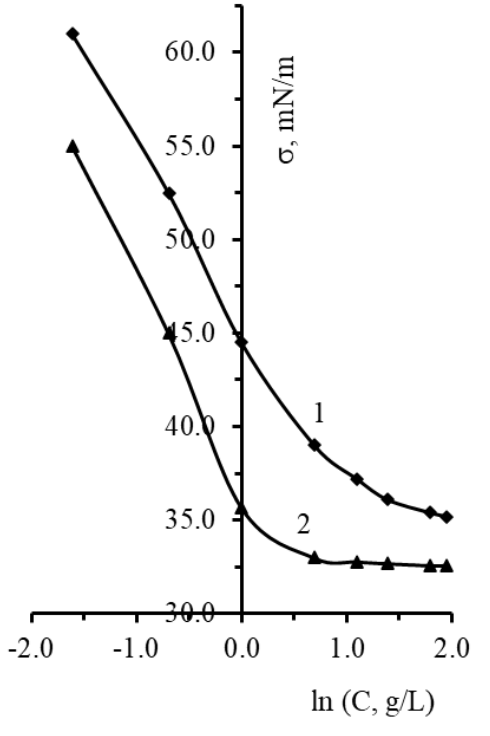


Fig. 7: Surface tension isotherms of aqueous solutions FCA-Na (soap) (1) and cationic surfactant FCA-3-DMAPA (2) at T=298.15 K.

Table 4: Micelle formation parameters, size, and zeta potential of colloidal particles in aqueous solution of the surfactants. T = 298.15 K. σ(H_2O) = 72.8 mN/m.

Surfactant	CMC, g/l	σ_{CMC}, mN/m	Π_{CMC}, mN/m	D_{CMC}, nm	ζ_{CMC}, mV
FCA-3-DMAPA	2.0	33.0	39.8	95	+71
FCA-Na (soap)	2.7	36.0	36.8	210	-77

Table 5: Adsorption parameters of the surfactants.

Surfactant	$\Gamma_{max}\times10^6$, mol/m^2	A_{min}, nm^2	C_{20}, g/l	pC_{20}	CMC/C_{20}
FCA-3-DMAPA	4.8	0.35	0.24	0.62	8.3
FCA-Na (soap)	3.9	0.43	0.50	0.30	5.4

Consequently, micelle formation in FCA-3-DMAPA surfactant solution occurs at a relatively lower concentration compared to FCA-Na (soap). These findings indicate that the hydrophobicity of FCA-3-DMAPA surfactant molecules is higher than that of FCA-Na (soap) molecules. It should be noted, that the σ_{CMC} value for FCA-3-DMAPA is higher than that of alkylpolyglucoside (26.9 mN/m), ethoxylated fatty alcohol (28.6 mN/m),[31] oleate (at pH 10, 25 mN/m) and sodium laurate (at pH 9, 22 mN/m),[29] as well as C_{12-14}-(ethylene oxide)$_2$-sulfate (26.5 mN/m).[44] At the same time, the σ_{CMC} of FCA-3-DMAPA surfactant is lower than that of sodium hexanoate (at pH 6–10) and C_{12}-(propylene oxide)$_{4-12}$-sulfate (40.0–33.7 mN/m).[29,45,46]

From the tabulated data, it follows that the maximum adsorption value of FCA-3-DMAPA is higher than that of FCA-Na (soap). For this reason, the area occupied by a single molecule in the saturated adsorption layer (A_{min}) of FCA-3-DMAPA is smaller than that of FCA-Na (soap) (Table 4). These findings indicate that FCA-3-DMAPA molecules adopt a more compact conformation, stabilized by hydrophobic interactions between hydrocarbon radicals, compared to FCA-Na (soap). In terms of A_{min}, the FCA-3-DMAPA surfactant is close to octylethylammonium chloride (0.34 nm²), sodium dodecyl sulfate, and sodium n-dodecylbenzenesulfonate (0.33 nm²).[47] However, the A_{min} of FCA-3-DMAPA is smaller than that of cetylpyridinium chloride (0.46 nm²), octylphenol ethylene glycol ethers (0.53–0.80 nm²),[47] ethoxylated fatty alcohol (0.44 nm²),[31] and C_2-sulfate (0.53 nm²).[45,46]

The parameter Π_{CMC} demonstrates the ability of a surfactant to reduce the surface tension of water, and the CMC/C_{20} parameter indicates if the surfactant preferably adsorbs to the surface or aggregates into micelles.[31,48] A high CMC/C_{20} ratio shows a high adsorption capacity of the surfactant at the water/air interface, while small ratio indicates a tendency to micelle formation.[48]

CMC/C_{20} for synthesized FCA-3-DMAPA cationic surfactant is lower than that of alkylethoxylated fatty alcohol (13.6),[31] C_{12-14}-(Ethylene oxide)$_2$-Sulfate (17.5),[44,48] C_{12}-(Propylene oxide)$_{4-12}$-Sulfate (11.6/42.2),[45,46,48] but it is close to the value of alkylpolyglucoside (6.3).[31]

The relatively low values of pCMC and CMC/C_{20} for the FCA-3-DMAPA surfactant indicate that molecules of this surfactant prefer to form micelles rather than adsorb at the water/air interface.[29,31,48]

3.7 Influence of the cationic surfactant FCA-3-DMAPA on water contact angle on the surface of Teflon

Fig. 8a shows the effect of the cationic surfactant FCA-3-DMAPA on the water contact angle of a Teflon (Polytetrafluoroethylene) surface. As seen from the figure, with increasing surfactant concentration, the water contact angle decreases monotonically from 101° (for water) to 42.8°. A more pronounced decrease in the contact angle occurs after reaching the CMC (2.0 g/L).

In an aqueous medium, the surface of Teflon acquires a negative charge due to the dissociation of carboxyl groups that remain on the surface after the polymerization process.[49]

The effect of a surfactant mixture – ethoxylated fatty alcohol (AE), alkylpolyglucoside (APG), and sodium soap (Na-soap) – on the water contact angle of a Teflon surface was studied.[31] It was found that among the two-component surfactant mixtures, the AE:APG (2:1) system exhibited the best wetting properties in the concentration range of 0.0004–0.001 mol/dm³, reducing the water contact angle up to 47.6°.

In three-component surfactant mixtures, the best results were obtained for the AE:APG:Na-soap (1:1:1) system in the concentration range of 0.008–0.001 mol/dm³, where the water contact angle decreased to 44.2°.

Among the known wetting agents for Teflon surfaces, silicon-based surfactants, particularly trisiloxanes,[50] should also be noted, which allow to reduce the water contact angle on Teflon surfaces up to 50°.

To elucidate the mechanism of adsorption of cationic surfactant molecules on the Teflon surface, the effect of the concentration of the FCA-3-DMAPA surfactant solution on the electrokinetic (zeta) potential of the Teflon suspension in

water was investigated (Fig. 8b). The figure shows that in the aqueous medium the Teflon surface acquires a weak negative charge (ζ ≈ –10 mV), and as the surfactant concentration increases, the negative charge decreases, becomes neutralized, and subsequently turns into a positive charge (charge reversal).

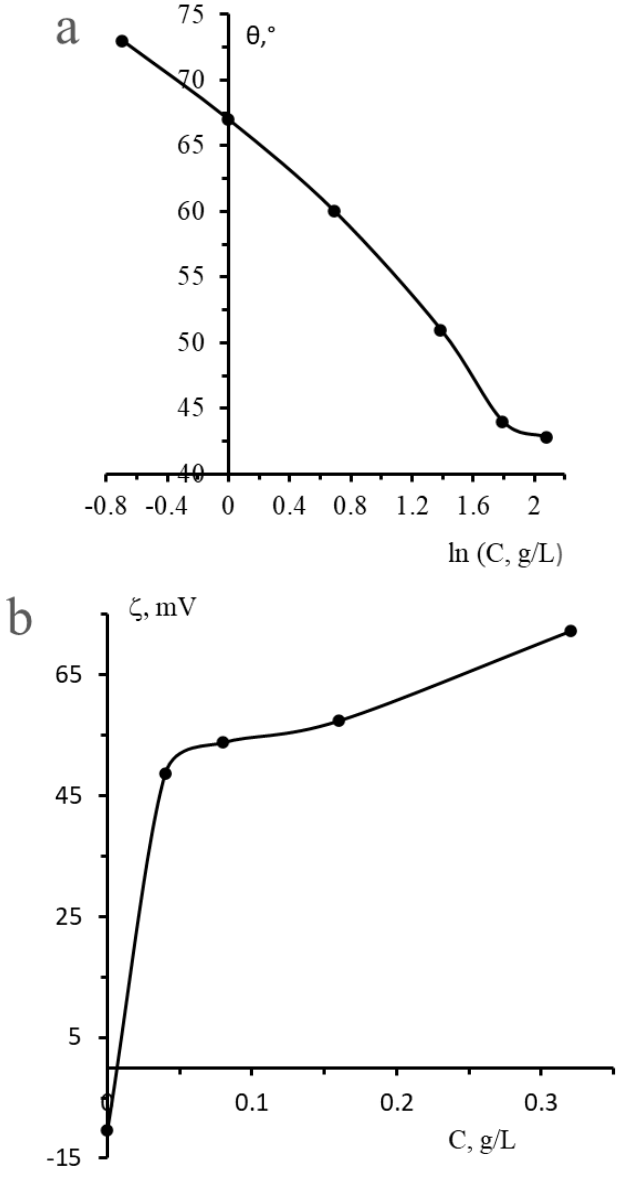


Fig. 8: Influence of the concentration of cationic surfactant FCA-3-DMAPA on the water's contact angle on the surface of Teflon (a) and zeta-potential of the teflon's suspention (b).

Thus, taking into account the experimental values, the decrease in the water contact angle on the Teflon surface in the presence of the FCA-3-DMAPA surfactant (Fig. 8a) can be explained as follows. When the Teflon plate is immersed in the FCA-3-DMAPA solution, the cationic surfactant molecules initially interact with the negatively charged Teflon surface via electrostatic attraction and adsorb onto the solid surface. As a result, the negative charge of the Teflon surface decreases, and subsequently, the surface becomes neutralized. With further adsorption, the surfactant molecules bind to the neutral surface through hydrophobic interactions, which ultimately renders the Teflon surface positively charged. With increasing concentration of the surfactant, the number of cationic surfactant molecules adsorbed on the Teflon surface increases, thereby enhancing the positive surface charge (Fig. 8b).

As the surface charge of Teflon increases, its hydrophilic properties are also enhanced, improving the interaction of the solid surface with water molecules. All these processes improve the wettability of the Teflon surface by water, leading to a decrease in the contact angle. Thus, our study demonstrated that the cationic surfactant FCA-3-DMAPA is highly effective in wetting hydrophobic Teflon surfaces.

3.8 Influence of the cationic surfactant FCA-3-DMAPA on the stability of the oil-in-water emulsion

Fig. 9 and Fig. S1 present the results of the study on the effect of the cationic surfactant FCA-3-DMAPA on the stability of industrial oil-in-water emulsions. As can be seen from the figures, the emulsion stability depends on the surfactant concentration, and relatively stable oil-in-water emulsions are formed in FCA-3-DMAPA surfactant solutions at concentrations of not less than 2.0 g/L.

Under these conditions, the emulsion stability after 4 hours reaches approximately 90 %. The formation of a stable emulsion is ensured by the development of an adsorption layer of the cationic surfactant FCA-3DMAPA at the oil/water interface. This layer possesses a certain strength and elasticity (a structural-mechanical barrier) as well as a positive charge (an electrostatic stabilization factor).[51,52] Such interfacial layers prevent the coalescence of oil droplets within the emulsion. The results of the emulsion stability study are in good agreement with the data on the adsorption of the cationic surfactant FCA–3-DMAPA at the water/air interface. A more stable emulsion is formed in the region of the critical micelle concentration of this surfactant (Table 4). Thus, our study demonstrates that the cationic surfactant FCA–3-DMAPA can be effectively employed as both an emulsifier and an emulsion stabilizer.

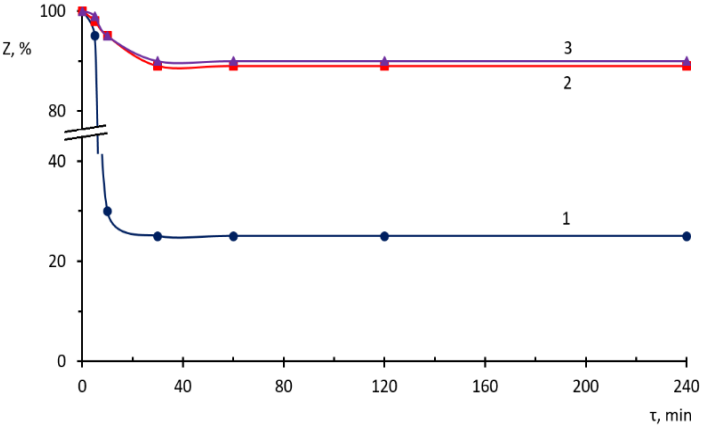


Fig. 9: Influence of the concentration of cationic surfactant FCA-3-DMAPA on the stability of the industrial oil-in-water emulsion. Surfactant's concentration (g/L): 0.5 (1); 2.0 (2) and 4.0 (3).

3.9 Coagulation of kaolin suspension's particles with cationic surfactant FCA-3-DMAPA

The coagulation properties of the cationic surfactant FCA-3-DMAPA were studied using kaolin suspension. The results are presented in Fig. 10.

As can be seen from the figure, kaolin particles spontaneously (in the absence of surfactant) sediment very slowly, and after 45 minutes the residual turbidity of the suspension is approximately 32 % (curve 1, Fig. 10). While in the presence of cationic surfactant FCA-3-DMAPA, the sedimentation rate of suspension particles increases significantly, and at a concentration of 20 g/t suspension, in 10 minutes after the addition of surfactant, the residual turbidity decreases to 20 % (curve 4, Fig. 10). After 45 minutes, the residual turbidity is 10 %. This means that during this time approximately 90 % of the kaolin suspension particles sediment.

The increase in the sedimentation rate of kaolin suspension particles in the presence of cationic surfactant FCA-3-DMAPA can be explained by the adsorption of surfactant molecules on the surface of suspension particles through an electrostatic mechanism.[39,40]

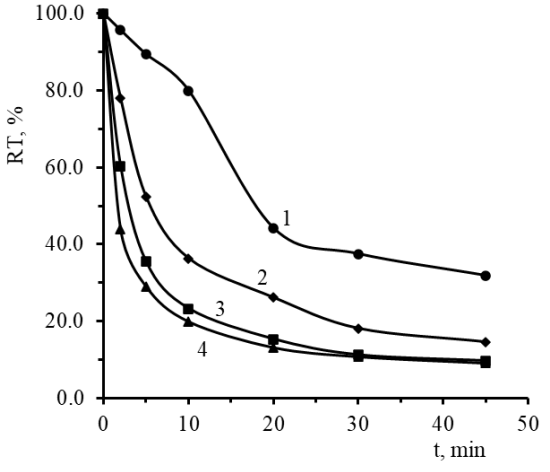


Fig. 10: Influence of cationic surfactant FCA-3-DMAPA on the flocculation of kaolin suspension particles. Concentration of surfactant (g/t of suspension): 0 (1); 6 (2); 12 (3) and 20 (4). C (kaolin suspension) = 0.3 wt. %.

Fig. 11 shows the influence of the cationic surfactant concentration on the zeta-potential of kaolin suspension particles. The figure demonstrates that kaolin particles have a negative charge (ζ = –20 mV), and with increasing surfactant concentration in the suspension, the zeta-potential of kaolin particles increases.

particles. The figure demonstrates that kaolin particles have a negative charge (ζ = –20 mV), and with increasing surfactant concentration in the suspension, the zeta-potential of kaolin particles increases.

At a surfactant concentration of 0.01 g/L, the zeta-potential turns to zero (Fig. 11), as a result of which the electrostatic repulsion between kaolin particles disappears, while the attractive forces, on the contrary, increase. The suspension particles coagulate and sediment at the bottom of the vessel.

Comparison with the flocculant – copolymer N, N-dimethyl-N, N-diallylammonium chloride with N, N-dimethylacrylamide (DMDAAC-DMAA) shows that the dosage of cationic surfactant FCA-3-DMAPA is approximately 1.8 times less than that of the specified flocculant.[40]

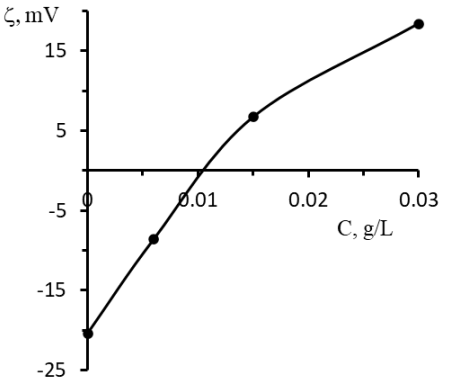


Fig. 11: Influence of Cationic Surfactant FCA-3-DMAPA concentration on the zeta-potential of kaolin suspension particles.

3.10 Study of biocidal properties of the cationic surfactant FCA-3-DMAPA

In order to determine the area of application, the biocidal properties of the synthesized cationic surfactant were also studied in relation to SRB that cause microcorrosion.[53-56] As can be seen from Fig. S2, in the control sample (C) (without of surfactant), the bacteria develop freely and adhere to the wall of the test tube.

As a result, a black film with a metallic luster form on the surface of the tube. It should be noted that SRB began to develop on the 10th day after the start of the experiment. In the presence of the optimal concentration of FCA-3-DMAPA surfactant, SRB completely die and precipitate to the bottom of the test tube. The study results showed that the FCA-3-DMAPA surfactant completely (100 %) suppresses the growth and development of SRB at a concentration of not less than 0.05 wt. % (Fig. S2). The biocidal effect of the surfactant was observed throughout the entire testing period.

The surfaces of most microbial cells and bacteria carry an overall negative charge.[57-59] Therefore, taking this assumption into account, the following mechanism of SRB growth suppression in the presence of FCA-3-DMAPA surfactant can be proposed. When the surfactant is added to the SRB medium, surfactant molecules adsorb onto the surface of bacteria through an electrostatic mechanism.[55,56,60]

As a result, an adsorption layer is formed on the surface of the bacterial membrane, possessing a certain thickness, strength, and elasticity and stabilized by intermolecular hydrophobic interactions. Such an adsorption layer limits the access of oxygen and nutrients to the inner part of the microorganism. All this ultimately leads to the death of the

microorganism. At the same time, according to the authors,[61-64] many surfactants are capable of penetrating the phospholipid bilayer, which also results in membrane destruction and the death of the microorganism.

Thus, our study showed that the cationic surfactant FCA-3-DMAPA exhibits bactericidal properties against SRB at a minimum concentration of 0.05 wt. % and can be used as a biocidal compound for the protection of metallic equipment and reinforced concrete structures from microbiological corrosion. The advantages of this surfactant compared to polymeric biocides[55,56,58-60] are that the cationic surfactant FCA-3-DMAPA is more accessible and can be synthesized from Renewable raw materials - a Residue of Sunflower Oil production.

4. Conclusion

The composition of technical vegetable oil obtained by hydrolysis of sunflower oil production residues and extraction was determined by IR and NMR spectroscopy, gas chromatography, and mass spectrometry. It was established that the composition of the technical vegetable oil is complex and includes nine types of fatty carboxylic acids (FCA).

By amidation of a mixture of FCA with 3-dimethylaminepropyl amine, followed by quaternization of the tertiary amine group with hydrochloric acid, a new cationic surfactant FCA-3-DMAPA was synthesized, and the optimal reaction conditions were determined. The composition of the synthesized new cationic surfactant was confirmed by IR and NMR spectroscopy.

It was determined that at critical micelle concentration, the average size of colloidal particles of the cationic surfactant FCA-3-DMAPA in aqueous solution is 95 nm, and the electrokinetic (zeta) potential is +71 mV.

It was shown that the cationic surfactant FCA-3-DMAPA is an effective wetting agent and can reduce the water contact angle on the surface of teflon from 101° to 43°.

The study demonstrated that the cationic surfactant FCA-3-DMAPA possesses emulsifying and coagulating properties. Therefore, this surfactant can be used as an emulsifier for stabilizing oil-in-water emulsions and as a coagulant for water purification from dispersed kaolin particles.

It was also established that the cationic surfactant FCA-3-DMAPA exhibits biocidal properties against sulfate-reducing bacteria and completely suppresses their growth at a concentration of not less than 0.05 wt. %.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRediT Statement

K. Zh. Abdiyev: Writing – Review & Editing, Supervision, Project administration, Investigation, Funding acquisition. **B. B. Sadykov:** Writing – Review & Editing, Investigation, Formal analysis, Data curation. **Chien-Hsiang Chang:** Supervision, Investigation, Formal analysis, Software. **M. B. Zhursumbayeva:** Investigation, Resources, Funding acquisition. **N. Zh. Seitkaliyeva:** Methodology, Investigation, Formal analysis, Resources, **G. K. Kussainova:** Investigation, Software, Data curation.**Z. N. Kambarova:** Methodology, Data curation, Formal analysis. **Zh. Toktarbay:** Supervision, Resources, Project administration.

References

[1] T. Curstedt, A. Calkovska, J. Johansson, New generation synthetic surfactants, *Neonatology*, 2013, **103**, 327-330, doi: 10.1159/000349942.

[2] P. Raffa, D. A. Z. Wever, F. Picchioni, A. A. Broekhuis, Polymeric surfactants: synthesis, properties, and links to applications, *Chemical Reviews*, 2015, **115**, 8504-8563, doi: 10.1021/cr500129h.

[3] H. Wang, W. Guo, C. Zheng, D. Wang, H. Zhan, Effect of temperature on foaming ability and foam stability of typical surfactants used for foaming agent, *Journal of Surfactants and Detergents*, 2017, **20**, 615-622, doi: 10.1007/s11743-017-1953-9.

[4] D. P. Sachdev, S. S. Cameotra, Biosurfactants in agriculture, *Applied Microbiology and Biotechnology*, 2013, **97**, 1005-1016, doi: 10.1007/s00253-012-4641-8.

[5] M. Abdurrahman, M. S. Kamal, R. Ramadhan, A. Daniati, A. Arsad, A. F. Abdul Rahman, N. Rita, Ecofriendly natural surfactants in the oil and gas industry: a comprehensive review, *ACS Omega*, 2023, **8**, 41004-41021, doi: 10.1021/acsomega.3c04450.

[6] A. Karnwal, S. Shrivastava, Abdel Rahman Mohammad Said Al-Tawaha, G. Kumar, R. Singh, A. Kumar, A. Mohan, Yogita, T. Malik, Microbial biosurfactant as an alternate to chemical surfactants for application in cosmetics industries in personal and skin care products: a critical review, *BioMed Research International*, 2023, **2023**, 2375223, doi: 10.1155/2023/2375223.

[7] H. A. Shehata, A. A. Abd El-wahab, A. A. Hafiz, I. Aiad, M. A. Hegazy, Syntheses and characterization of some cationic surfactants, *Journal of Surfactants and Detergents*, 2008, **11**, 139-144, doi: 10.1007/s11743-008-1064-8.

[8] L. Y. Zakharova, T. N. Pashirova, S. Doktorovova, A. R. Fernandes, E. Sanchez-Lopez, A. M. Silva, S. B. Souto, E. B. Souto, Cationic surfactants: self-assembly, structure-activity correlation and their biological applications, *International Journal of Molecular Sciences*, 2019, **20**, 5534, doi: 10.3390/ijms20225534.

[9] R. S. Makkar, K. J. Rockne, Comparison of synthetic surfactants and biosurfactants in enhancing biodegradation of polycyclic aromatic hydrocarbons, *Environmental Toxicology and Chemistry*, 2003, **22**, 2280-2292, doi: 10.1897/02-472.

[10] J. Zembrzuska, I. Budnik, Z. Lukaszewski, Monitoring of selected non-ionic surfactants in river water by liquid chromatography–tandem mass spectrometry, *Journal of Environmental Management*, 2016, **169**, 247-252, doi: 10.1016/j.jenvman.2015.12.034.
[11] V. S. Nagtode, C. Cardoza, H. K. Ahmad Yasin, S. N. Mali, S. M. Tambe, P. Roy, K. Singh, A. Goel, P. D. Amin, B. R. Thorat, J. N. Cruz, A. P. Pratap, Green surfactants (biosurfactants): a petroleum-free substitute for Sustainability─Comparison, applications, market, and future prospects, *ACS Omega*, 2023, **8**, 11674-11699, doi: 10.1021/acsomega.3c00591.
[12] A. Veeramanoharan, S.-C. Kim, A comprehensive review on sustainable surfactants from CNSL: chemistry, key applications and research perspectives, *RSC Advances*, 2024, **14**, 25429-25471, doi: 10.1039/d4ra04684f.
[13] P. Phani Kumar, R. Paramashivappa, P. J. Vithayathil, P. V. Subba Rao, A. Srinivasa Rao, Process for isolation of cardanol from technical cashew (*Anacardium occidentale* L.) nutshell liquid, *Journal of Agricultural and Food Chemistry*, 2002, **50**, 4705-4708, doi: 10.1021/jf020224w.
[14] J. H. P. Tyman, I. E. Bruce, Surfactant properties and biodegradation of polyethoxylates from phenolic lipids, *Journal of Surfactants and Detergents*, 2004, **7**, 169-173, doi: 10.1007/s11743-004-0300-3.
[15] A. A. Obuebite, W. I. Eke, T. Udoh, Evaluation of modified cashew nutshell liquid as natural surfactants for chemical flooding in sandstone oil reservoirs, *Journal of Engineering and Applied Science*, 2022, **69**, 114, doi: 10.1186/s44147-022-00167-4.
[16] H. dos Santos Nascimento, S. R. da Luz, B. do Amaral Crispim, G. Lampugnani, F. Kummrow, A. Barufatti, By-products of the cashew nut production chain as alternatives for the development of larvicides: a review, *Waste and Biomass Valorization*, 2024, **15**, 3217-3237, doi: 10.1007/s12649-023-02365-4.
[17] P. Kirilov, H. Azira, T. Benvegnu, L. Lemiègre, Cationic surfactants based on renewable raw resources – characterization and applications, *NanoSpain*, Malaga, Spain, March, 2010, **37**, 23-26.
[18] A. Abdulameer Salman, Cationic carbohydrate-based surfactants derived from renewable resources: Trends in synthetic methods, *Results in Chemistry*, 2022, **4**, 100602, doi: 10.1016/j.rechem.2022.100602.
[19] N. S. Han, T. Heidelberg, A. A. Salman, Spacer effect on triazole-linked sugar-based surfactants, *Journal of Dispersion Science and Technology*, 2017, **38**, 105-109, doi: 10.1080/01932691.2016.1144513.
[20] M. Tabandeh, A. A. Salman, E. W. Goh, T. Heidelberg, R. S. D. Hussen, Renewable resources-based approach to biantennary glycolipids, *Chemistry and Physics of Lipids*, 2018, **212**, 111-119, doi: 10.1016/j.chemphyslip.2018.01.011.
[21] Karlheinz Hill and Catherine LeHen-Ferrenbach, Chapter 1, *Sugar-based surfactants: Fundamentals and Applications*, CRC Press, Malaga, 2008, 1-21, ISBN: 978-1-4200-5166-7 (Hardcover).
[22] P. Misiak, K. A. Wilk, T. Kral, E. Woźniak, H. Pruchnik, R. Frąckowiak, M. Hof, B. Różycka-Roszak, New gluconamide-type cationic surfactants: interactions with DNA and lipid membranes, *Biophysical Chemistry*, 2013, **180**, 44-54, doi: 10.1016/j.bpc.2013.06.010.
[23] A. A. Salman, M. Tabandeh, T. Heidelberg, R. S. Duali Hussen, Functional glycolipid-crown-ethers by click chemistry, *Carbohydrate Research*, 2015, **406**, 41-45, doi: 10.1016/j.carres.2014.12.015.
[24] B. Różycka-Roszak, E. Woźniak, P. Misiak, R. Frąckowiak, K. A. Wilk, Thermodynamic properties of new gluconamide-based cationic surfactants in aqueous solution: Experimental and modeling approaches, *The Journal of Chemical Thermodynamics*, 2013, **66**, 1-8, doi: 10.1016/j.jct.2013.06.012.
[25] A. M. Al-Sabagh, N. G. Kandil, O. Ramadan, N. M. Amer, R. Mansour, E. A. Khamis, Novel cationic surfactants from fatty acids and their corrosion inhibition efficiency for carbon steel pipelines in 1M HCl, *Egyptian Journal of Petroleum*, 2011, **20**, 47-57, doi: 10.1016/j.ejpe.2011.06.007.
[26] K. Z. Abdiyev, B. B. Sadykov, M. B. Zhursumbayeva, N. Z. Seitkaliyeva, C. H. Chang, G. K. Kussainova, Z. N. Kambarova, Z. Toktarbay, New nonionic surfactants from renewable raw materials-sunflower oil production waste, *ES Materials & Manufacturing*, 2025, **29**, 1679, doi: 10.30919/mm1679.
[27] S. Z. Abidin, D. Patel, B. Saha, Quantitative analysis of fatty acids composition in the used cooking oil (UCO) by gas chromatography− mass spectrometry (GC–MS), *The Canadian Journal of Chemical Engineering*, 2013, **91**, 1896-1903, doi: 10.1002/cjce.21848.
[28] K. Mac Namara, J. Howell, Y. Huang, A. Robbat, Analysis of gin essential oil mixtures by multidimensional and one-dimensional gas chromatography/mass spectrometry with spectral deconvolution, *Journal of Chromatography A*, 2007, **1164**, 281-290, doi: 10.1016/j.chroma.2007.07.042.
[29] A. Atrafi, M. Pawlik, Surface tension and gas dispersion properties of fatty acid solutions, *Minerals Engineering*, 2016, **85**, 138-147, doi: 10.1016/j.mineng.2015.11.006.
[30] J. T. Davies, E. K. Rideal, Interfacial phenomena, *Angewandte Chemie,* 1963, **77**, 276, doi: 10.1002/ange.19650770625.
[31] P. Szumała, A. Mówińska, Perfectly wetting mixtures of surfactants from renewable resources: the interaction and synergistic effects on adsorption and micellization, *Journal of Surfactants and Detergents*, 2016, **19**, 437-445, doi: 10.1007/s11743-016-1793-z.
[32] D. K. Chattoraj, K. S. Birdi, *Adsorption and the Gibbs Surface Excess*, Springer, New York, 2013, 274, ISBN-10: 1461583357.
[33] J. T. Davies, The distribution of ions under a charged monolayer, and a surface equation of state for charged films, *Proceedings of the Royal Society of London Series A Mathematical and Physical Sciences*, 1951, **208**, 224-247, doi: 10.1098/rspa.1951.0156.
[34] K. S. Birdi, Surface and Colloid Chemistry. Principles and Applications. *CRC Press*, 2009, doi: 10.1201/b10154.

[35] M. J. Rosen, D. S. Murphy, Effect of the nonaqueous phase on interfacial properties of surfactants. 2. Individual and mixed nonionic surfactants in hydrocarbon/water systems, *Langmuir*, 1991, **7**, 2630-2635, doi: 10.1021/la00059a039.
[36] O. Y. Berezin, Y. I. Tur'yan, L. Kogan, I. Kuselman, A. Shenhar, Practical limitations in determining vegetable oil acid values by a novel pH-metric method, *Journal of the American Oil Chemists' Society*, 1997, **74**, 1339-1341, doi: 10.1007/s11746-997-0067-3.
[37] S. G. Li, H. Zhang, W. T. Xue, A novel method for the determination of acid value of vegetable oils, *European J. Lipid Sci. & Technology*, 2007, **109**, 1088-1094, doi: 10.1002/ejlt.200700058.
[38] N. A. Glukhareva, A. S. Kazbayeva, A. O. Adilbekova, A. B. Yertayeva, Effect of surfactant mixtures on the stability of emulsions, *Bulletin of the L. N. Gumilyov Eurasian National University. Chemistry. Geography. Ecology series,* 2020, **132**, 43-51, doi: 10.32523/2616-6771-2020-132-3-43-51.
[39] B. Zhang, H. Su, X. Gu, X. Huang, H. Wang, Effect of structure and charge of polysaccharide flocculants on their flocculation performance for bentonite suspensions, *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2013, **436**, 443-449, doi: 10.1016/j.colsurfa.2013.07.017.
[40] K. Z. Abdiyev, Z. Toktarbay, A. Z. Zhenissova, M. B. Zhursumbaeva, R. N. Kainazarova, N. Nuraje, The new effective flocculants–Copolymers of N, N-dimethyl-N, N-diallyl-ammonium chloride and N, N-dimethylacrylamide, *Colloids and Surfaces A*: *Physicochemical and Engineering Aspects*, 2015, **480**, 228-235, doi: 10.1016/j.colsurfa.2015.04.025.
[41] J. M. Thompson, *Infrared Spectroscopy*, Pan Stanford Publishing Pte. Ltd., Danvers, 2018, 211, ISBN: 9814774782.
[42] E. Moore, Fourier transform infrared spectroscopy (FTIR): Methods, Analysis, and Research Insights, Nova Science Publishers, Inc., New York, 2017, 140, ISBN: 9781536104011.
[43] Donald L. Pavia, Gary M. Lampman, George S. Kriz, James R. Vyvyan, Chapters 2 and 5, *Introduction to spectroscopy*, Gengage Learning, Washington, 2009, 14-107, 215-290, ISBN-13: 978-1-285-46012-3.
[44] M. Lv, Y. Zhou, S. Wang, F. Han, B. Xu, Effects of the polypropylene oxide number on the surface properties of a type of extended surfactant, *Journal of Surfactants and Detergents*, 2018, **21**, 335-341, doi: 10.1002/jsde.12039.
[45] J. J. Liu, M. A. A. Gasmalla, P. Li, R. Yang, Enzyme-assisted extraction processing from oilseeds: Principle, processing and application, *Innovative Food Science & Emerging Technologies*, 2016, **35**, 184-193, doi: 10.1016/j.ifset.2016.05.002.
[46] X. Liu, Y. Zhao, Q. Li, J. Niu, Surface tension, interfacial tension and emulsification of sodium dodecyl sulfate extended surfactant, *Colloids and Surfaces A*: *Physicochemical and Engineering Aspects*, 2016, **494**, 201-208, doi: 10.1016/j.colsurfa.2016.01.037.
[47] Y. G. Frolov, A. S. Grodskii, Appendix, *Laboratory Work and Problems in Colloid Chemistry*, Chimia, Moscow, 1986, 211-213. ISBN: 541.18(076.5).
[48] Y. Gagnon, H. Mhemdi, F. Delbecq, E. Van Hecke, Extended surfactants and their tailored applications for vegetable oils extraction: an overview, *Ocl*, 2021, **28**, 7, doi: 10.1051/ocl/2020062.
[49] T. R. Desai, S. G. Dixit, Coadsorption of cationic–nonionic surfactant mixtures on polytetra fluoroethylene (PTFE) surface, *Journal of Colloid and Interface Science*, 1996, **179**, 544-551, doi: 10.1006/jcis.1996.0248.
[50] J. Radulovic, K. Sefiane, M. E. R. Shanahan, Spreading and wetting behaviour of trisiloxanes, *Journal of Bionic Engineering*, 2009, **6**, 341-349, doi: 10.1016/S1672-6529(08)60142-0.
[51] E. B. A. Hinderink, L. Sagis, K. Schroën, C. C. Berton-Carabin, Sequential adsorption and interfacial displacement in emulsions stabilized with plant-dairy protein blends, *Journal of Colloid and Interface Science*, 2021, **583**, 704-713, doi: 10.1016/j.jcis.2020.09.066.
[52] G. Simonsen, J. Kjølaas, P. R. Leinan, H. Schümann, Literature review on surface-active components in emulsions and foams: Theory and modelling efforts, *Geoenergy Science and Engineering*, 2023, **230**, 212156, doi: 10.1016/j.geoen.2023.212156.
[53] H. Liu, Y. F. Cheng, Microbial corrosion of X52 pipeline steel under soil with varied thicknesses soaked with a simulated soil solution containing sulfate-reducing bacteria and the associated galvanic coupling effect, *Electrochimica Acta*, 2018, **266**, 312-325, doi: 10.1016/j.electacta.2018.02.002.
[54] I. A. Jones, L. T. Joshi, Biocide use in the antimicrobial era: a review, *Molecules*, 2021, **26**, 2276, doi: 10.3390/molecules26082276.
[55] K. Z. Abdiyev, G. K. Kussainova, M. N. Mohamad Ibrahim, M. B. Zhursumbayeva, N. Z. Seitkaliyeva, T. M. Seilkhanov, D. N. Shakhmetova, Z. Toktarbay, A polyampholyte based on itaconic acid and [(3-methacryloylamino)propyl]-trimethylammonium chloride: synthesis and study of biocidal properties, *ES Materials & Manufacturing*, 2024, **25**, 1218, doi: 10.30919/esmm1218.
[56] K. Z. Abdiyev, M. B. Zhursumbayeva, N. Z. Seitkaliyeva, G. K. Kussainova, M. N. Mohamad Ibrahim, D. N. Shakhmetova, M. Y. Yermaganbetov, Z. Toktarbay, Synthesis and characterization of N, N-dimethylacrylamide and [(3-methacryloyl-amino)propyl] trimethylammonium chloride copolymers: kinetics, reactivity, and biocidal properties, *Engineered Science*, 2024, **30**, 1217, doi: 10.30919/es1217.
[57] L. Timofeeva, N. Kleshcheva, Antimicrobial polymers: mechanism of action, factors of activity, and applications, *Applied Microbiology and Biotechnology*, 2011, **89**, 475-492, doi: 10.1007/s00253-010-2920-9.
[58] F. Siedenbiedel, J. C. Tiller, Antimicrobial polymers in solution and on surfaces: overview and functional principles, *Polymers*, 2012, **4**, 46-71, doi: 10.3390/polym4010046.
[59] H. Qiu, Z. Si, Y. Luo, P. Feng, X. Wu, W. Hou, Y. Zhu, M. B. Chan-Park, L. Xu, D. Huang, The mechanisms and the applications of antibacterial polymers in surface modification on medical devices, *Frontiers in Bioengineering and Biotechnology*, 2020, **8**, 910, doi: 10.3389/fbioe.2020.00910.

[60] K. Z. Abdiyev, Z. Toktarbay, B. Y. Orynbayev, M. B. Zhursumbaeva, N. Z. Seitkaliyeva, U. Nakan, Structure formation in suspensions and biocidal properties of copolymer of 2-acrylamido-2-methylpropanesulfonic acid and allylamine, *Materials Today: Proceedings*, 2022, **71**, 13-17, doi: 10.1016/j.matpr.2022.06.050.
[61] J. Guan, L. P. Xia, L. Y. Wang, J. F. Liu, J. D. Gu, B. Z. Mu, Diversity and distribution of sulfate-reducing bacteria in four petroleum reservoirs detected by using 16S rRNA and dsrAB genes, *International Biodeterioration & Biodegradation*, 2013, **76**, 58–66, doi: 10.1016/j.ibiod.2012.06.021.
[62] W. Chin, C. Yang, V. W. L. Ng, Y. Huang, J. Cheng, Y. W. Tong, D. J. Coady, W. Fan, J. L. Hedrick, Y. Y. Yang, Biodegradable broad-spectrum antimicrobial polycarbonates: investigating the role of chemical structure on activity and selectivity, *Macromolecules*, 2013, **46**, 8797-8807, doi: 10.1021/ma4019685.
[63] J. Hoque, P. Akkapeddi, V. Yadav, G. B. Manjunath, D. S. S. M. Uppu, M. M. Konai, V. Yarlagadda, K. Sanyal, J. Haldar, Broad spectrum antibacterial and antifungal polymeric paint materials: synthesis, structure-activity relationship, and membrane-active mode of action, *ACS Applied Materials & Interfaces*, 2015, **7**, 1804-1815, doi: 10.1021/am507482y.
[64] U. Nakan, S. Bieerkehazhi, B. Tolkyn, G. A. Mun, M. Assanov, M. E. Nursultanov, R. K. Rakhmetullayeva, K. Toshtay, E. S. Negim, A. Ydyrys, Synthesis, Characterization and Antibacterial Application of Copolymers Based on *N*,*N*-Dimethyl Acrylamide and Acrylic Acid, *Materials*, 2021, **14**, 6191, doi: 10.3390/ma14206191.

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