REPUBLIC OF AZERBAIJAN

On the rights of the manuscript

ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT AND ANALYTICAL APPLICATION OF NEW METHODS FOR THE PRECONCENTRATION OF IRON (III)

Speciality: 2301.01 – "Analytical chemistry"

Field of science: Chemistry

Applicant: **Esmira Jalil Eyyubova**

Baku – 2026

The work was performed at the Department of Analytical Chemistry of Baku State University.

Scientific supervisors: Doctor of Chemical Sciences, Professor **Famil Musa Chyragov**

Doctor of Chemical Sciences, Professor **Khalil Jamal Nagiyev**

Official opponents: Corresponding Memmer of ANAS, Doctor of Chemical Sciences, Professor **Tofig Abbasali Aliyev**

Doctor of Chemical Sciences, Professor **Naila Allahverdi Verdizade**

Doctor of Philosophy in Chemistry, Associate Professor **Aydin Mahammad Pashajanov**

Dissertation council FD 2.16 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at Baku State University

Chairman of the Dissertation council: Doctor of Chemical Sciences, Associate Professor **Fuad Shamsaddin Karimli**

Scientific secretary of the Dissertation council: Doctor of Philosophy in Chemistry **Fidan Nariman Bahmanova**

Chairman of the scientific seminar: Doctor of Chemical Sciences, Professor **Ali Zal Zalov**

BAKI DÖVLƏT UNİVERSİTETİ
ELMİ KATİB
SCIENTIFIC SECRETARY

GENERAL CHARACTERISTICS OF THE WORK

Relevance and degree of development of the topic. Modern technologies for removing pollutants of various natures from natural objects and man-made systems are usually characterized by high costs, significant energy costs and the need for subsequent disposal of toxic waste. Therefore, there is an increasing need to develop effective, selective, economically valuable and environmentally friendly materials and methods of purification that can provide both the separation of contaminants and their subsequent determination.

In many cases, the components are present in trace amounts, complicating their direct determination with existing analytical methods. Therefore, preconcentration methods are particularly important, as they increase analytical sensitivity and ensure reliable results when studying complex multicomponent systems[1]. Among the numerous preconcentration methods, sorption and extraction methods are the most widely used, characterized by high efficiency, relative ease of implementation, and the ability to be combined with various instrumental analytical methods[2].

Due to their technological simplicity, safety, and cost-effectiveness, sorption methods retain enduring interest in environmental protection, analytical chemistry, and industrial ecology. In recent years, sorption techniques have been widely used to purify aqueous samples and other objects from various contaminants, including various metal ions. The potential of sorption is determined by a combination of parameters such as the sorbent's porous structure, chemical nature, and number of active functional groups. Various sorbents have been studied and used in this regard, including natural clays, activated carbons, carbon molecular sieves, biomass, and agricultural waste, as

[1]Opara, I.J., Ukoha, P.O., Onunze, E.O. Extractive spectrophotometric determination of Fe(III) and Co(II) from steel sample using azo ligand 1,5-dimethyl-2-phenyl-4-[(E)-(2,3,4-trihydroxylphenyl)diazenyl]-1,2-dihydro-3H-pyrazole-3-one // International Journal of Chemical, Material and Environmental Research, - 2018, v. 5, № 1, - p. 148-154.

[2] Didukh, S.L., Muhina, A.N., Losev, V.N. Sorption-photometric determination of iron(II) in drinking waters using titanium dioxide based sorbents modified with polihexamethylene guanidine ferrozine or ferene // Chemistry, - 2015, № 8, - p. 35-44.

well as commercial materials such as activated alumina, ion-exchange polymer resins, and zeolites.

The determination of trace ions, especially iron(III), in various matrices of natural and industrial origin is of particular importance. A wide range of analytical methods for determining Fe(III) have been developed, among which extraction methods occupy a special place due to their high sensitivity, selectivity, and reproducibility.

In connection with the above, the development and research of new methods that combine high efficiency of pollutant removal with the possibility of selective and accurate determination of iron (III) is a promising scientific and practical task that is of great importance for environmental safety, analytical chemistry and industrial monitoring.

Object and subject of the study. The primary focus of this dissertation is on various complex objects containing low amounts of iron(III) ions. The research focuses on the development of new methods for the sorption and extraction preconcentration of iron(III), the study of iron(III) ion sorption by synthesized sorbents, and its complexation with the resulting ligands.

Goals and objectives of the research. The main goal of the work is developing new preconcentration methods for determining small amounts of iron(III) in samples of various origins.

To achieve this goal, the following tasks were completed:

– Sorbents consisting of maleic anhydride and its copolymer with styrene were synthesized, some of the sorbents were modified with the appropriate reagent, and their composition and temperature stability were studied;

– The key sorption and desorption parameters of the resulting sorbents on iron (III) were studied;

– Two new reagents were synthesized, their single crystals were grown, and their composition, structure, and key crystal cell parameters were determined;

– An extraction preconcentration technique for iron (III) was studied, and the key extraction parameters were determined;

– The developed techniques were used to determine the iron(III) content in various complex samples.

Research methods. To achieve the objectives set in the dissertation, the methods of IR-, UV and visible spectroscopy, thermal and X-ray structural analysis, as well as SEM/EDS were used.

The main provisions of the defense. Effective methods for Fe(III) preconcentration have been developed using synthetic sorbents S_1-S_9 based on maleic anhydride styrene copolymer, as well as pre-modified sorbents S_{10} and S_{11}. A comprehensive analysis of sorption processes was conducted: the sorption kinetics, equilibrium, and the influence of accompanying components were studied, and the applicability of the Langmuir, Freundlich, and Dubinin-Radushkevich models was demonstrated. New reagents R_3 and R_4 were synthesized and characterized by X-ray analysis methods. Extraction-photometric methods for Fe(III) determination using reagents R_1, R_3, and R_4 were developed. The methods were successfully tested on real samples, with the accuracy of the results confirmed by ICP-OES analysis.

Scientific novelty of the research. New iron(III) preconcentration methods were developed and optimized. New sorbents were synthesized and subsequently modified with an appropriate reagent. The composition of sorbents and key sorption parameters were studied using various analytical methods. New reagents were synthesized, and their single crystals were grown. X-ray diffraction analysis was used to determine the key cell parameters. The resulting reagents were used for the extractive preconcentration of iron(III).

Theoretical and practical significance of the study. This study contributes to the development of practical analytical chemistry by expanding our understanding of Fe(III) sorption preconcentration and extraction analysis methods. The results of the study provide the potential for improving sorption and extraction models, as well as theoretical approaches, for developing new materials and methods for determining various metals. The developed methods can be applied to monitoring and purifying water from Fe(III) contaminants, which is important for ensuring environmental safety. The data obtained can be applied in various industrial sectors, including environmental monitoring, natural resource processing, and agricultural product analysis. The development of effective sorbents and extraction reagents opens

new possibilities for application in analytical laboratories and industrial processes. The results of this study can be used to develop cost-effective and environmentally friendly technologies for the preconcentration and separation of Fe(III) in complex samples.

Approbation and implementation. 9 articles and 23 abstracts were published on the dissertation topic. The dissertation materials were presented and discussed at the following conferences:

– Materials of the XII International Scientific Conference "Current Problems of Chemistry" for doctoral students, masters and young researchers dedicated to the 95th anniversary of the birth of the National Leader Heydar Aliyev (Baku, 2018);

– 1st International Science and Engineering Conference (Baku, 2018);

– III International Scientific Conference of Young Researchers (Baku, 2019);

– Chemistry, Chemical Technology and Ecology: Science, Production, Education. Abstracts of the reports of the international scientific and practical conference and school for young scientists (Makhachkala, 2018);

– Materials of the XIII International Scientific Conference "Current Problems of Chemistry" for doctoral students, masters and young researchers dedicated to the 96th anniversary of the birth of National Leader Heydar Aliyev (Baku, 2019);

– XI All-Russian Conference on Environmental Analysis with International Participation "Ecoanalytics-2019" (Perm, 2019);

– International Scientific and Methodological Conference "Chemistry: Achievements and Prospects", dedicated to the 85th anniversary of Academician Givi Tsintsadze (Tbilisi, 2019);

– 1st International Symposium on Recent Advances in Fundamental and Applied Sciences (ISFAS-2021) (Turkey, 2021);

– 6th International Turkic World Conference on Chemical Sciences and Technologies (ITWCCST) (Bakı, 2022);

– International Conference: Modern Problems of Theoretical&Experimental Chemistry, Devoted to the 90th anniversary of Academician Rafiga Aliyeva (Baku, 2022);

– Materials of the Republican scientific conference on "Modern approaches in petrochemistry and chemical technology" (Baku, 2023);

– International scientific conference "Chemistry-achievements and perspectives" dedicated to the 90th anniversary of the birth of academician Givi Tsintsadze (Tbilisi, 2023);

– International conference: Modern trends in physics (Baku, 2023);

– XX International Conference. Spectroscopy of Coordination Compounds (Kuban, 2024);

– Chemical Science and Education: Problems and Development Prospects. Collection of scientific papers from the international conference (Makhachkala, 2024);

– Proceedings of the LXII reporting scientific conference of teachers and research staff of VSUIT for 2023 (Voronezh, 2024);

– Kyiv Conference on Analytical Chemistry: Modern Trends (Kyiv, 2024);

– Materials of the International Scientific and Practical Conference on the Current Status and Development Prospects of Science and Technology in the Era of the Fourth Industrial Revolution, dedicated to the 102nd anniversary of the birth of the National Leader Heydar Aliyev (Baku, 2025);

– IV Republican Scientific Conference on Chemistry and Chemical Technology for doctoral students, masters and young researchers dedicated to the 102nd anniversary of the birth of National Leader Heydar Aliyev (Baku, 2025);

– MacroFrontiers 2025: 3rd international Scientific Conference on Macromolecular Compounds (Baku, 2025);

– 2nd International conference. Modern problems of theoretical and experimental chemistry dedicated to the 120th anniversary of academician Yusif Mammadaliyev (Baku, 2025).

Name of the organization where the dissertation was completed. The dissertation was completed at the Department of Analytical Chemistry, Faculty of Chemistry, Baku State University.

The applicant's personal contribution to the research conducted. The applicant directly participated in conducting the research. They collected and analyzed the latest literature on the subject, drew conclusions, and synthesized sorbents and new reagents. They applied the resulting compounds to the determination of trace amounts of iron(III) ions and presented their own insights in articles related to the research.

The volume and structure of the dissertation. The dissertation consists of an introduction, five chapters, results, and a bibliography. The bibliography includes references to 153 sources. The dissertation is written in A4 format and comprises 191 pages. The main body of the dissertation consists of 206462 characters (excluding spaces, figures, tables, and bibliography). The dissertation includes 30 figures and 42 tables.

The first chapter (49225 characters) provides an overview of modern methods for sorption and extractive preconcentration and determination of Fe(III), as well as the characteristics and mechanisms of action of the sorbents and reagents used.

The second chapter (64628 characters) presents the experimental portion of the work, including the preparation of solutions and reagents, the synthesis and identification of the reagents and sorbents, and their physicochemical and sorption characterization, including a study of their interaction with Fe(III).

Chapter three (56913 characters) presents the results of a study of Fe(III) ion sorption by synthesized sorbents, including an examination of the isotherms, kinetics, and energy characteristics of the sorption process.

Chapter four (20247 characters) presents a study of the extraction preconcentration and spectrophotometric determination of Fe(III) using organic reagents R_1, R_3, and R_4, as well as the optimization of extraction and complexation conditions.

Chapter five (22345 characters) presents the application of the developed methods for determining Fe(III) content in complex samples.

SUMMARY

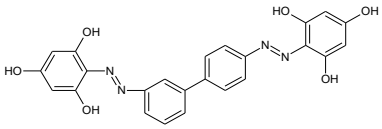
Synthesis of reagents and complexes

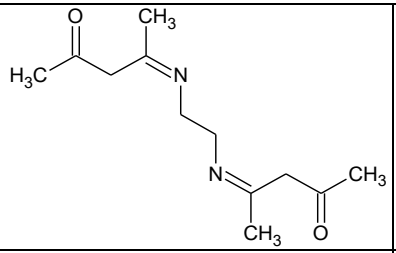
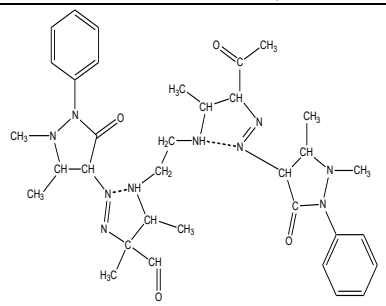
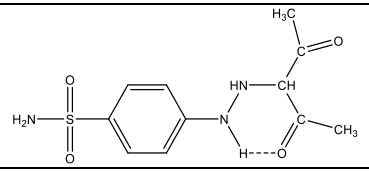
The following organic reagents were used in the work: 2,2`-1([1,1`-diphenyl]-4,4`-diylbis(diazine-2,1-diyl)bis(benzene-1,3,5-triol) (R_1), 4,4'-(ethane-1,2-diylbis(azanylidene))bis(pentan-2-one) (R_2), 4-((E)-(2-((2-((1R)-2-(1,5-dimethyl-3-oxo-2-phenyl pyrazolidin-4-yl)-4,4,5-trimethyl-4,5-dihydro-1H-1λ4,2λ4,3-triazol-1-yl)ethyl)amino)-4-oxopentan-3-yl) diazenyl)-1,5-dimethyl-2-phenylpyrazolidin-3-one (R_3) and 4-[2-(2,4-dioxypentan-3-yl)hydrazinyl]benzene sulfonamide (R_4). The names, structural formulas, and relative molecular weights of the reactants are shown in Table 1.

The synthesis of reagents R_1-R_4 was carried out according to a known method.

A complex of Fe(III) with the ligand 4-((E)-(2-((2-((1R)-2-(1,5-dimethyl-3-oxo-2-phenyl pyrazolidin-4-yl)-4,4,5-trimethyl-4,5-dihydro-1H-1λ4,2λ4,3-triazol-1-yl)ethyl)amino)-4-oxopentan-3-yl) diazenyl)-1,5-dimethyl-2-phenylpyrazolidin-3-one R_3 was synthesized.

Table 1. Names, structural formulas and other characteristics of the reagents used.

Name of the organic reagent	Structural formula	Brutto formula and relative molecular mass
2,2`-1([1,1`-diphenyl]-4,4`-diylbis(diazin-2,1-diyl)bis(benzene-1,3,5-triol) (R_1)		$C_{24}H_{12}O_6N_4$ 458
4,4'-(ethane-1,2-diylbis(azanylidene))bis(pentan-2-one) (R_2)		$C_{12}H_{20}O_2N_2$ 224

		
4-((E)-(2-((2-((1R)-2-(1,5-dimethyl-3-oxo-2-phenylpyrazolidin-4-yl)-4,4,5-trimethyl-4,5-dihydro-1H-1λ4,2λ4,3-triazol-1-yl)ethyl)amino)-4-oxopentan-3-yl)diazenyl)-1,5-dimethyl-2-phenylpyrazolidin-3-one (R_3)		$C_{34}H_{40}N_{10}O_4$ 652,76
4-[2-(2,4-dioxypentan-3-yl)hydrazinyl]benzene sulfonamide (R_4)		$C_{11}H_{13}N_3O_4S$ 283,3

The reagents were synthesized at the Department of Analytical Chemistry at Baku State University. All other reagents were purchased from sigmaaldrich.com. All reagents used in the experiments were of analytical grade.

Identification of reagents and complexes

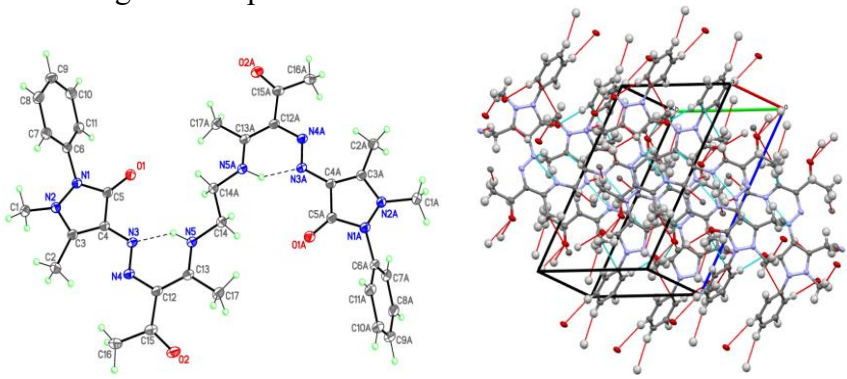
The molecular and crystal structures of ligands R_3 and R_4 were studied using X-ray diffraction analysis, and the main parameters of the crystal cell were presented.

A study of the structure of reagent R_3 shows that the compound's molecular formula is $C_{34}H_{40}N_{10}O_4$. At T=100 K, the corresponding angles are: a=5.83293(7), b=10.25650(11), c=14.49887(15),

α=73.3216(15)°, β=81.7835(17)°, γ=79.0740(16)°, V=812.228(17) Å^3. The single crystal dimensions are 0.2x0.21x0.27 Å. The crystal was found to have a triclinic syngony. The spatial structure of P -1, z=1, $\rho_{(calc)}$=1.334 g/cm^3, μ= 0.742 mm^{-1}. The diffraction coefficients R=0.0523(3118) and wR_2=0.1510(3420). The structural formula of the reagent R_3 with numbered atoms is shown in Fig. 1 (a).

As can be seen from Fig. 1 (a), the ethylenediamine molecules were transferred to the single crystal during crystallization. The ethylenediamine atoms in the crystal structure are numbered as follows: N(5)-C(14)-C(14A)-N(5A). The torsion angle N(5)-C(14)-C(14A) is 107.71(14) Å.

The interatomic distances in the R_3 ligand structure confirm the presence of a stable covalent structure with bond lengths characteristic of aromatic and heterocyclic fragments. The bond lengths between the C–C and C–N atoms are typical of conjugated and saturated systems, indicating the absence of significant distortions in the molecular geometry. The C=O bonds, with a length of 1.23 Å, indicate the presence of carbonyl groups with a pronounced double bond character. The participation of nitrogen atoms in conjugation and the stabilization of the molecular structure are explained by the presence of N–N and N–C bonds. Overall, these parameters confirm the ordered structure and are in good agreement with the predicted geometry of the synthesized class of organic compounds.



(a) **(b)**

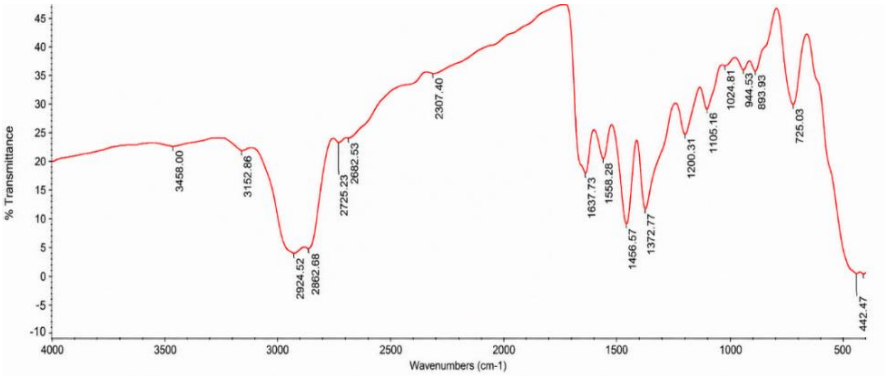
Fig. 1. (a) - Molecular structure of ligand R_3; (b) - Crystal structure of ligand R_3.

As can be seen from the figure, six-membered rings C(12), N(4), N(3), H(5), N(5), C(13) and C(12)A, N(4)A, N(3)A, H(5)A, N(5)A, C(13)A are formed in the system due to intramolecular hydrogen bonding. The torsion angle between the N(4)-C(12)-C(13)-C(17) bonds is 173.38(13), and between the N(3)-N(4)-C(12)-C(13) bonds is 5.9(2). The difference in the torsion angles from 0^0 indicates the possibility of free rotation of the substituent groups around the C(12) and C(13) atoms. This, in turn, creates the possibility of forming complex compounds due to the coordination of these functional groups with metal ions.

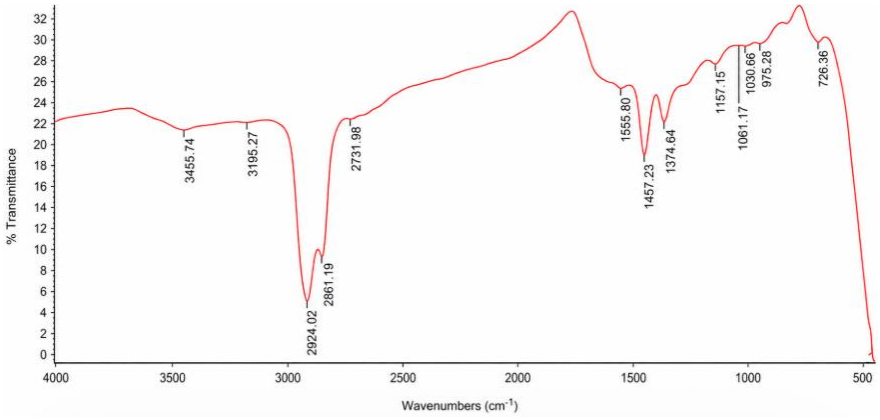
The crystal structure of the reagent (Fig. 1(b)) shows that each molecule is linked to other molecules by intermolecular bonds, which are formed between the N(3)-H(3) and N(3A)-H(3A) atoms. The molecule is packed via intermolecular hydrogen bonds.

The crystallographic data for R_3 have been deposited with the Cambridge Crystallographic Data Centre (CCDC) under accession number 2335935.

An iron(III) complex with ligand R_3 was synthesized. The structure of the synthesized Fe(III) complex with R_3 was studied using infrared spectroscopy. The corresponding IR spectra of the ligand and its complex are shown in Fig. 2(a, b).



(a)



(b)

Fig. 2. IR spectrum: (a) ligand R_3; (b) Fe(III)-R_3 complex

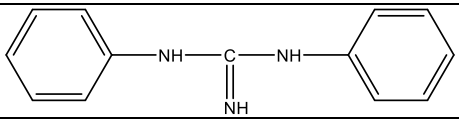
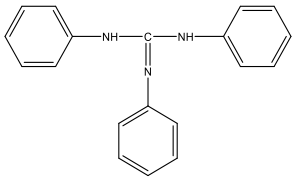
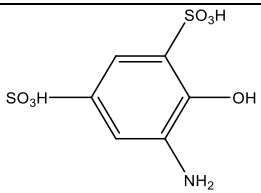
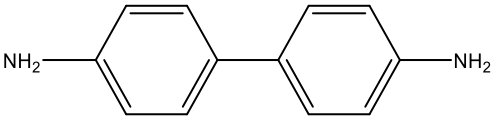
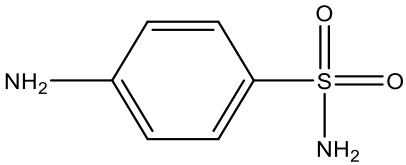
From the IR spectra in Fig. 2 (a,b), one can see a number of significant changes in the position and intensity of the main bands, which confirm the formation of a complex compound of the obtained ligand with Fe(III). In the spectrum of ligand R_3 in Fig. 2 (a) before complex formation, typical bands are observed corresponding to the band of valence vibrations of aromatic C–H bonds in the region of 3000–3100 cm^{-1}, bands of alkyl C–H groups in the region of 2850–2950 cm^{-1}, as well as an intense band in the region of ~1600–1650 cm^{-1}, which corresponds to vibrations of C=N or C=O groups. A band of the N–H group at 3200–3500 cm^{-1} is also observed in the spectrum, which is characteristic of the amine group of the ligand.

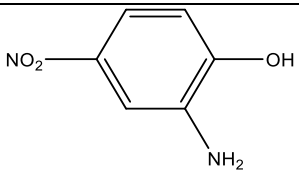
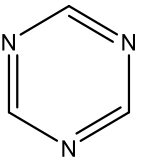
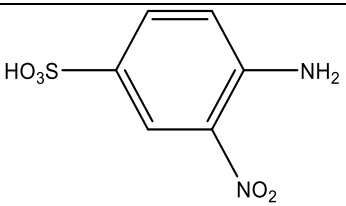
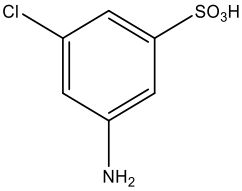
Figure 2.(b) shows that after the formation of the Fe(III)–R_3 complex, a number of characteristic shifts are observed in the IR spectrum. First, the C=N band shifts to lower frequencies and decreases slightly in intensity, indicating the participation of the nitrogen atom of this group in coordination with the Fe(III) ions. The most important indicator of complex formation is the appearance of bands in the 400–600 cm^{-1} region, which were absent from the ligand spectrum before complex formation. These bands correspond to vibrations of the Fe–N bond valence angles and thus confirm the coordination of the ligand to the iron ion.

Sorbent synthesis

The sorbents were synthesized using a known method. Table 2 lists the amines used to modify the polymer base.

Table 2. Amine fragments included in the copolymer macromolecule.

Sorbent symbol (Amine name)	Amine fragment	Reaction time, min
S_1 (N,N`- diphenylguanidine)		30-35
S_2 (Triphenylguanidine)		35-40
S_3 (2-amino-4,6-disulfonic acid)		25-35
S_4 (4,4`- diaminodiphenyl)		32-40
S_5 (4-aminobenzenesulfonamide) (streptocide)		20-25

S_6 (2-amino-4-nitrophenol)		35-40
S_7 (1,3,5- triazine)		35-40
S_8 (2-nitro-4-sulfoaniline)		25-30
S_9 (2-amino-4-chloro-6-sulfonic acid)		30-32

To increase the sorption capacity of the sorbents, they were modified using various reagents. In this dissertation, sorbents S_1 and S_8 were modified with reagent R_2. The resulting product, with the selected component ratio, was used as a sorbent for Fe(III) extraction and determination of its trace amounts in various natural and industrial samples.

Investigation of the obtained sorbents

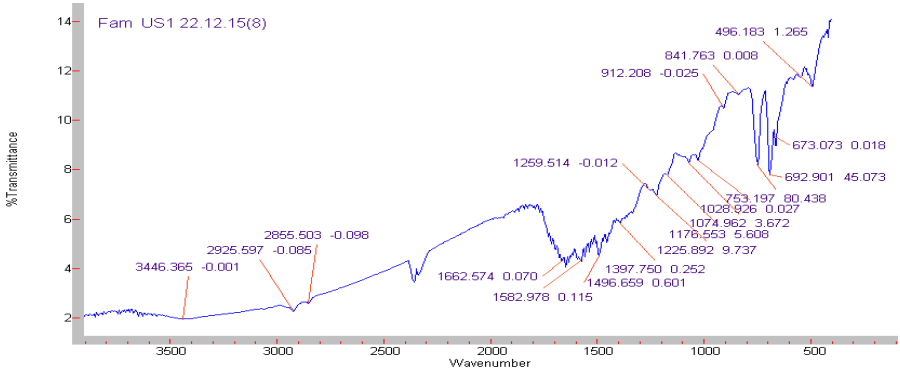
Fourier transform infrared spectroscopy (FT-IR) was used to establish the structure of the obtained sorbents.

Figure 3 (a,b) shows the IR spectra of the sorbent before and after sorption.

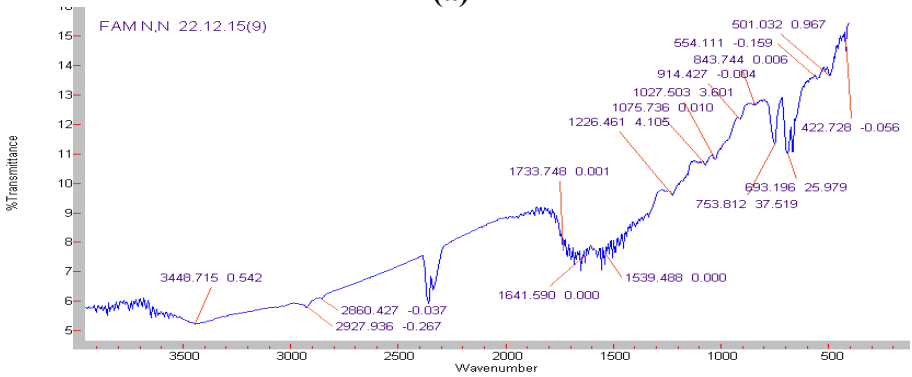
The IR spectrum of S_1 contains bands characteristic of the sorbent, related to vibrations of -OH groups at 3448 cm^{-1}, the carbonyl

group C=O at 1733 cm^{-1}, bands of the deformation vibration of the amino group -NH at 1641 cm^{-1}, bands corresponding to vibrations of -C-C bonds in the benzene ring at 1539 cm^{-1} and 1075-1027 cm^{-1} (Fig. 3 (a)).

The IR spectrum after adsorption contains the following absorptions: stretching vibration of the -OH group at 3446 cm^{-1}, deformation vibration of the -NH group at 1582 cm^{-1}, vibrations of the stretching -C-C- bonds in the aromatic ring at 1496 cm^{-1}, vibrations of the stretching bonds of the -NH group at 1357 cm^{-1}, vibrations in the -C-C- bonds of the aromatic ring at 1176-1028 cm^{-1} (Fig. 3 (b)).



(a)

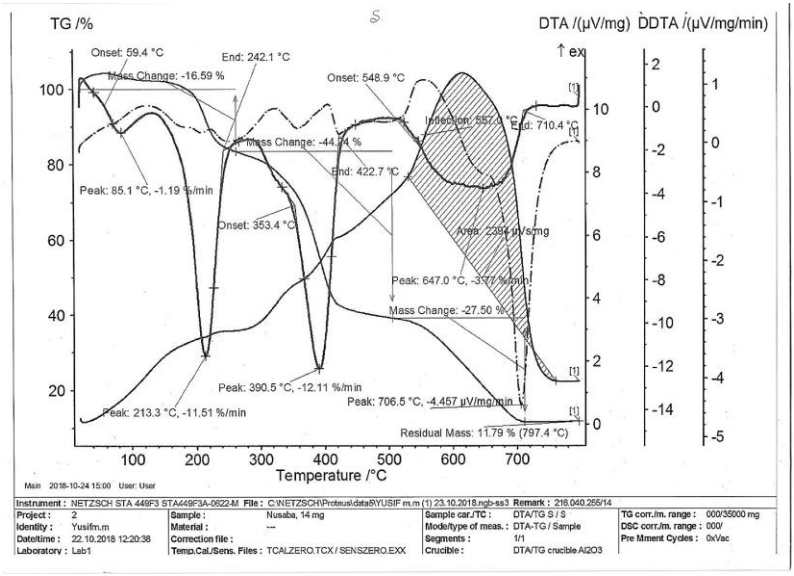


(b)

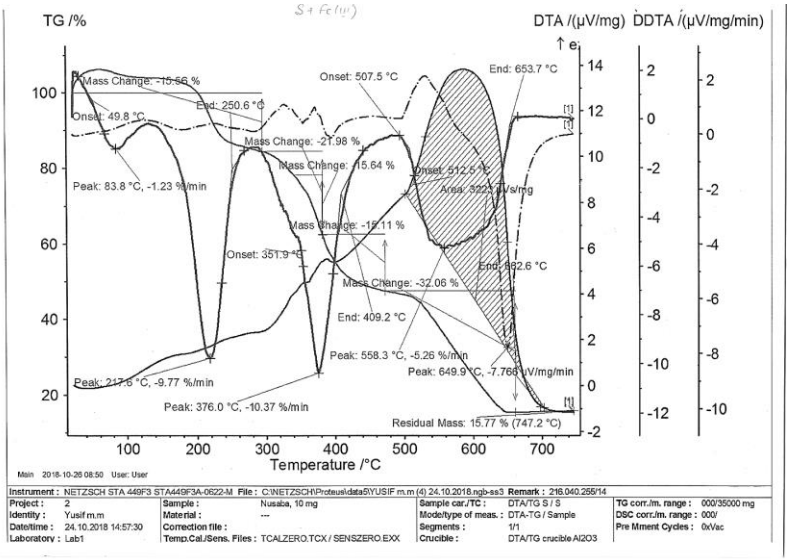
Fig. 3. (a) IR spectrum of sorbent S_1; (b) IR spectrum of the complex of sorbent S_1 with iron(III).

A thermogravimetric analysis (TGA) study of sorbent S_1 (Fig. 4(a)) revealed that its thermal decomposition occurs in several stages. The TG/DTA curves show four stages of decomposition for individual products. The first stage, spanning a temperature range from 59 to 242°C, is characterized by a mass loss of approximately 16.6%. This loss is due to the evaporation of sorbed and bound water, as well as the removal of low-molecular-weight volatile compounds.

For S_1, the greatest mass loss of 44.24% is observed in the temperature range of 353-422°C, with a DTG peak at 390.5°C. A second stage of decomposition is observed in the temperature range of 549-710°C, with a mass loss of 27.5%. The differential thermal analysis (DTA) curve shows an exothermic effect with a maximum at 647°C. The residual mass of the sample is 11.79%. This indicates the formation of a heat-resistant inorganic or carbon residue. After the sorption of iron ions (Fig. 4 (b)) at the initial stage, in the temperature range of 50–251 °C, a mass loss of about 15.6% is recorded, caused by the desorption of sorbed moisture and the evaporation of volatile components.



(a)



(b)

Fig. 4. Thermal analysis curves for sorbent S_1: (a) before sorption: (b) after sorption.

The main stage of thermal destruction occurs in the temperature range of 351–409 °C, accompanied by a mass decrease of approximately 32.1%. The maximum destruction rate in this range is achieved at 376 °C. In the high-temperature region (508–654 °C), further destruction of more thermally stable structural fragments occurs, which is manifested in additional mass loss and a pronounced exothermic effect on the differential thermoanalytical recording curve with a maximum at 649.9 °C. After the sorption of metal ions, the greatest mass loss for S_1+Fe(III) at 507.5-653.7 ℃ is 32.6% with a DTG peak of 558.3 ℃. The intensity of this thermal effect indicates oxidation of the carbonaceous residue and the onset of structural reorganization processes in the material. Upon completion of thermal decomposition at approximately 747°C, the residual mass is 15.77%, indicating the formation of a significant amount of heat-resistant residue, presumably containing inorganic components or carbonization products.

The surface morphology and topography of the reagent-modified sorbent S_{10} were studied using a JSM-6610LV SEM. Figure 5

shows the SEM results of the surface layer of sorbent S_{10} before and after modification with reagent R_2.

In the SEM image, spots indicate a rough and porous sorbent surface, which leads to an increase in its sorption capacity. Figure 5 shows that the pores and surface of the sorbent are coated with R_2, resulting in a smooth surface.

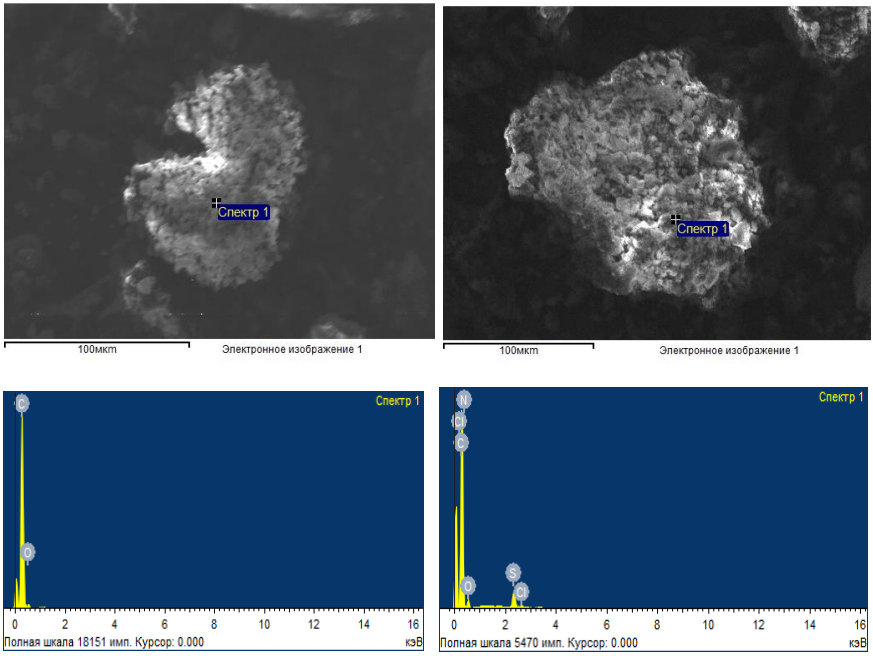


Fig. 5. SEM/EDS results of the surface layer of modified sorbent S_{10}.

Based on the EDS peaks, it can be concluded that the main elements present in sorbent S_{10} are C and O atoms. EDS also confirms the presence of N atoms in the modified form.

During the study, the UV-visible spectrum of the iron(III) complex was examined before and after modification with the reagent (Fig. 6).

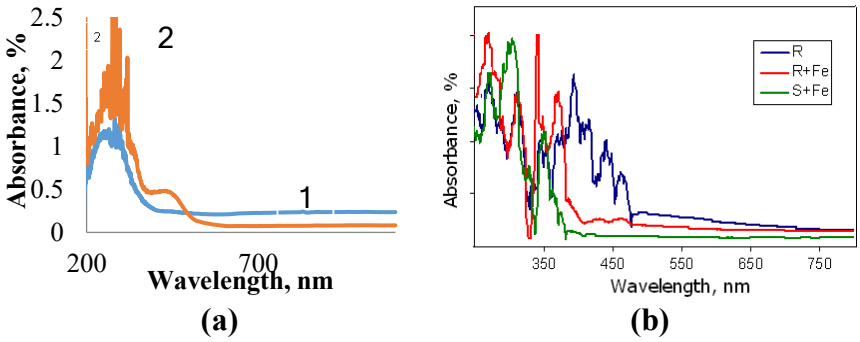


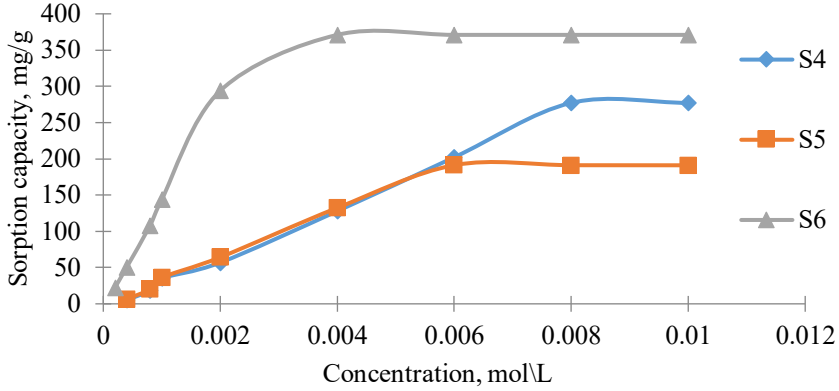
Fig. 6. Ultraviolet-visible spectra: (a) 1-S_1+Fe(III), 2- S_{10}+Fe(III), (b)-S_{10}+Fe(III).

The results of the ultraviolet-visible spectra (Fig. 6) show that the reagent-modified sorbent S_{10} (red line 2) exhibits higher adsorption capacity compared to the initial product S_1 (blue line 1), which can be explained by the fact that the number of active reaction groups involved in the modified product S_{10} is greater than that of S_1. Ultraviolet-visible spectra were recorded on a Specord 250 PLUS (AnalytikJena) 2010.

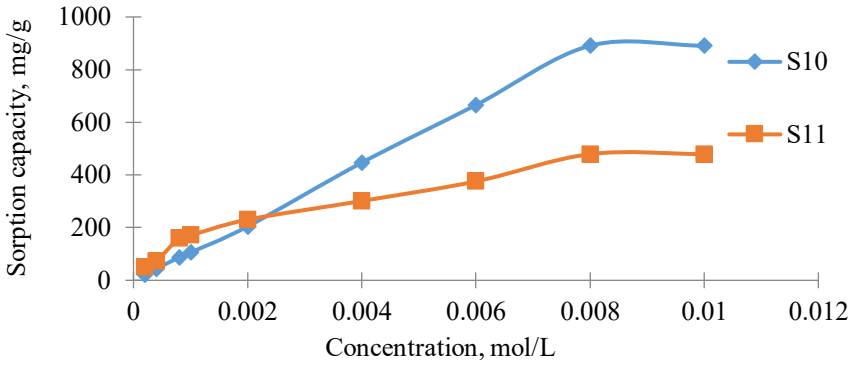
Sorption study of iron(III) ions using synthetic sorbents S_1-S_9

The effect of initial solution concentration on sorption was determined using multicomponent solution concentrations in the range of 0.0002-0.01 mol/L. Sorption isotherms were constructed based on the obtained data (Fig. 7 (a, b)).

It is evident that with increasing initial metal ion concentration in the solution, the sorption capacity and initial sorption rate increase (Fig. 7 (a)). This is due to an increase in the concentration gradient between the solution and the sorbent surface, which is the driving force for mass transfer and helps overcome diffusion resistance during metal ion sorption.



(a)



(b)

Fig. 7. Isotherms of sorption of iron (III) by sorbents: a) S_4, S_5 and S_6; (b) S_{10} and S_{11}.

Consequently, as the initial concentration increases, the driving force also increases, leading to increased sorption efficiency. Subsequently, after the system reaches saturation, the solution concentration will not significantly change the amount of ion sorbed due to a decrease in the number of active sites.

The sorption isotherms for S_{10} and S_{11} (Fig. 7 (b)) show that in both cases, the highest sorption is observed at a concentration of $8x10^{-3}$ M and amounts to 890.68 mg/g for sorbent S_{10} and 479.2 mg/g for S_{11}. As can be seen, sorption efficiency increases with increasing concentration and then remains constant. This can be explained by the fact

that the functionally active groups of the sorbent are completely saturated with iron (III) ions.

The extraction rates for the respective sorbents and the main sorption parameters are shown in Table 3.

Table 3. Main sorption parameters for the obtained sorbents.

Sorbent	Sorption capacity, mg/g	Sorption degree, %	pH_{opt}	μ, mol/L	Time, min.
S_1	404.88	91.75	5	0.4	30
S_2	267.8	86.99	4	0.2	60
S_3	373.31	87.3	5	0.2	60
S_4	277.2	91	5	0.2	90
S_5	191,28	91.9	5	0.2	120
S_6	371	95	4	0.2	120
S_7	367.21	85	5	0.2	90
S_8	348	90.7	5	0.2	120
S_9	331.61	91.1	5	0.2	90
S_{10}	890.68	95.75	5	0.4	120
S_{11}	479.2	94	4	0.2	150

A comparative analysis of the sorption properties of samples S_1–S_9 revealed that the studied sorbents are highly effective at extracting substances from solution; however, their performance varies significantly depending on the process conditions. Sample S_1 exhibited the highest sorption capacity, reaching 404.88 mg/g with a sorption rate of 91.75%. The process proceeded under relatively mild conditions: the optimal pH was 5. Ionic strengths of up to 0.4 mol/L did not affect the degree of sorption, and the time to achieve effective sorption was only 30 minutes. This demonstrates the high activity and rapid action of this sorbent. Samples S_3 (373.31 mg/g), S_6 (371 mg/g), and S_7 (367.21 mg/g) also demonstrated high sorption capacities.

Most of the studied sorbents demonstrated the best results in a slightly acidic environment at pH=4–5, indicating the important role of solution acidity in the sorption process. The time to reach maximum efficiency ranged from 30 to 120 minutes, demonstrating the different kinetics of sorption processes among the studied materials. Overall,

the study results demonstrate that all the studied sorbents exhibit high sorption activity and can be considered promising materials for solution purification.

After modifying sorbents S_1 and S_8 with the appropriate reagent, the resulting products (S_{10} and S_{11}) were used to study their sorption characteristics.

As can be seen from Table 3, a pH of 4-5 corresponds to the full capacity of the sorbent. Considering that at this pH, the sorbents are primarily in ionic form, it can be assumed that they exhibit sorption properties in this form. After 2 hours, sorption equilibrium is achieved.

In both cases, increasing the ionic strength in the range of 0.2-1.6 mol/L does not affect the sorption process. A subsequent increase in ionic strength leads to a decrease in sorbent capacity.

With increasing iron (III) concentration, an increase in sorbent capacity is observed. After a certain value, increasing the iron (III) content does not lead to an increase in the maximum capacity, which subsequently stabilizes. This can be explained by the fact that the functional groups within the macromolecule are completely saturated with metal ions.

A comparative study of the desorption of trivalent iron ions using mineral and organic acids of equal concentrations revealed that nitric acid possesses the highest desorption capacity (Table 3). This is explained by its high acidity and ability to effectively disrupt the coordination bonds between Fe(III) ions and the donor atoms of the sorbent's functional groups, as well as to form highly soluble iron nitrate complexes, which facilitates the transition of the metal into solution. Desorption results indicate that when using a 0.5 mol/L HNO_3 solution, more than 95% of the ions are desorbed.

The desorption process was also studied at various concentrations of the optimal eluent to determine the maximum concentration and volume at which the greatest amount of iron(III) is desorbed. For this purpose, the nitric acid content was varied from 0.5 to 2.0 mol/L. The results indicate that desorption capacity increases with increasing nitric acid content. The highest degree of deorption occurs at a concentration of 2.0 mol/L. Ultimately, it was found that using a 2.0 mol/L

concentrated nitric acid solution at a minimum volume provides optimal conditions for Fe(III) desorption, achieving a desorption rate of up to 97–98%. The results confirm the feasibility of effective regeneration of the synthesized sorbents and their potential for repeated use in extracting iron(III) from samples of various origins.

Sorption equilibrium study. Sorption isotherms

To explain the equilibrium relationship between the sorbent and sorbate and determine the maximum sorption capacity of the sorbent for iron(III) ions, several sorption isotherm models were studied. Results for the Langmuir and Dubinin-Radushkevich models are presented in Tables 4 and 5, respectively.

Table 4. Langmuir sorption isotherm parameters.

Sorbent	Sorption parameters			
	(q_{max}, mg/g)	(K_L, L/mg)	(R_L)	(R^2)
S_1	2.77	0.3	0.76	0.911
S_2	71.42	1.75	0.99	0.969
S_3	7.608	4.28	0.99	0.992
S_6	13.44	24.08	0.99	0.93
S_7	1.176	2.83	0.97	0.98
S_8	12.28	0.36	0.99	0.769
S_{11}	58.2	0.47	0.99	0.905

The applicability of isotherm models for explaining sorption processes was assessed by comparing the R_2 correlation coefficients. The closer the R_2 values are to unity, the better the model is at describing sorption. The results show that the linear relationship corresponds reasonably well to the experimental results, as confirmed by the high R_2 correlation coefficients.

The Langmuir constants and their R_2 correlation coefficients are given in Table 4. According to Langmuir theory, optimal sorption is observed when the R_L value lies in the range of 0-1. Table 4 shows that for sorbent S_1, R_L=0.76; for S_2, S_3, and S_6, R_L=0.99; for S_7, R_L=0.97; and for S_8, R_L=0.99. As can be seen, the R_L values for all sorbents are in the range of 0-1, indicating that the sorption process

proceeds favorably under the selected conditions. Thus, it can be argued that he Langmuir isotherm model provides an acceptable description of the sorption process for the studied sorbents.

Table 5. Parameters of the Dubinin-Radushkevich sorption isotherm

Sorbent	Sorption parameters			
	(q_s, mg/g)	(E, kJ/mol)	K_{D-R}, mol^2/kJ^2	(R^2)
S_1	5.65	2.8	$0.4 \cdot 10^{-5}$	0.738
S_2	221.4	2.89	$6 \cdot 10^{-8}$	0.801
S_3	291.2	2.8	$6 \cdot 10^{-8}$	0.933
S_4	16.11	0,4	$3 \cdot 10^{-6}$	0.921
S_5	8.89	1.61	$2 \cdot 10^{-7}$	0.846
S_6	384.25	3.5	$4 \cdot 10^{-8}$	0.882
S_7	73.4	0.11	$4 \cdot 10^{-5}$	0.939
S_8	7.42	5.1	$0.2 \cdot 10^{-7}$	0.886
S_9	6.62	2.5	$8 \cdot 10^{-8}$	0.930
S_{10}	8.47	7.142	$1 \cdot 10^{-8}$	0.521
S_{11}	8.47	7.142	$0,3 \cdot 10^{-7}$	0.931

The values of q_s, R_2, and K_{D-R} are given in Table 5. The quantitative characteristic of the Dubinin-Radushkevich model is the sorption energy E. The E value allows us to draw conclusions about the sorption mechanism. It is known that if E is between 8 and 16 kJ/mol, this indicates chemical sorption, and an E value below 8 kJ/mol indicates physical sorption. Thus, in our case, the E value for all sorbents is below 8 kJ/mol, indicating that physical sorption occurs between the sorbents and Fe(III) ions.

Study of the kinetic properties of Fe(III) ion sorption by synthesized sorbents

Sorption kinetics can be useful for describing sorption from a mechanistic perspective. In this study, we examined several kinetic models, including pseudo-first-order and pseudo-second-order mod-

els. The study showed that the pseudo-second-order model best describes the iron(III) ion sorption process (Table 6).

Table 6. Results of the pseudo-second-order model

	Pseudo-second order			
Sorbent	$q_{e(exp)}$, mg/g	k_2, (g/mg·h)	$q_{e(calc)}$, mg/g	(R^2)
S_1	182.216	0.125	200	1
S_2	267,8	0,005	200	1
S_3	373.33	0.059	363.44	1
S_4	277.2	0.016	111.11	1
S_5	191.28	0.007	173.91	1
S_6	373.33	1.36	435	1
S_7	361.27	0.004	500	0.999
S_8	91.33	0.0013	100	0.998
S_9	373.31	2.04	373	1
S_{10}	87.120	0.0023	76.92	0.991
S_{11}	150.7	0.00038	166.66	0.989

Based on the results of this kinetic model, it can be assumed that for almost all sorbents, the calculated $q_{(calc)}$ value is significantly closer to the experimental $q_{(exp)}$, indicating that the second-order model can be applied to describe the kinetic characteristics of Fe(III) sorption preconcentration by these sorbents.

Temperature is known to affect the rate and equilibrium of sorption. Therefore, to gain a more detailed understanding of the sorption mechanism, the effect of temperature on the sorption process was studied. As temperature changes, the rate of iron(III) sorption changes. This allows us to estimate the sorption energy.

To calculate the activation energy, the rate constants were calculated at various temperatures. Based on these data, the activation energies of the sorption process were calculated using the Arrhenius equation. The activation energy values are 12.557 kJ/mol for S_1, 42.878 kJ/mol for S_5, and 33.138 kJ/mol for S_{10}. The lowest Ea value for S_1 indicates a faster sorption process, while higher values for S_5 and S_{10} indicate a higher energy barrier to the process. The calculated

activation energy values allow us to draw conclusions about the mechanism of iron(III) sorption. In particular, an activation energy value above 20 kJ/mol suggests a chemical nature of sorption for sorbents S_5 and S_{10}, indicating that complexation between iron(III) ions and reactive groups in the sorbent structure predominates during the sorption process.

The effect of various ions on Fe(III) sorption

The results of studies reflecting information on how foreign ions affect Fe(III) sorption and the permissible amount of accompanying cations are given in Table 7.

Table 7. Effect of Foreign Ions on Fe(III) Sorption

Foreign ion	Acceptable quantity	Foreign ion	Acceptable quantity
Na(I)	5000	Ni(II)	200
K(I)	5000	Zn(II)	150
Ca(II)	800	W(VI)	100
Mg(II)	650	Cd(II)	100
Co(II)	500	Al(III)	50
Mn(II)	350	Cu(II)	50
Sr(II)	210	Cr(III)	50
Ba(II)	200	Pb(II)	40

The most permissible are the monovalent ions Na(I) and K(I), which have virtually no effect on the sorption process, due to their high complexation capacity and high hydration. Alkaline earth ions Ca(II), Mg(II), Sr(II), and Ba(II) have a weak effect, which is mainly due to the fact that the ionic strength of the solution changes. Transient divalent ions Mn(II), Co(II), Ni(II), Zn(II), and Cd(II) are able to partially compete with Fe(III) for the active sites of the sorbent, which leads to a moderate decrease in the permissible amounts, with Mn(II) having the least effect. Trivalent ions Al(III) and Cr(III) are among the most interfering due to their similar chemical nature to Fe(III), a tendency to hydrolysis, and the formation of strong surface complexes. The strongest influence is exerted by Cu(II), Pb(II) and W(VI) ions, which is due to their high

ability to form complexes and competitively bind with the reactive groups of the sorbent, as a result of which their permissible quantity is significantly limited.

Extraction-photometric analysis of iron (III) with reagents R_3 and R_4

The extraction capabilities of iron (III) with 4-((E)-(2-((2-((1R)-2-(1,5-dimethyl-3-oxo-2-phenylpyrazolidin-4-yl)-4,4,5-trimethyl-4,5-dihydro-1H-1λ4,2λ4,3-triazol-1-yl)ethyl)amino)-4-oxopentan-3-yl)diazenyl)-1,5-dimethyl-2-phenylpyrazolidin-3-one (R_3) and 4-[2-(2,4-dioxypentan-3-yl)hydrazinyl]benzenesulfonamide (R_4) were studied. The main factors influencing the extraction process, including the acidity of the medium, the nature of the organic solvent, the contact time of the phases, and the stability of the complex, were investigated. To improve extraction efficiency, various organic extractants were studied, with 1-butanol showing the best results, providing a high degree of extraction. The results are presented in Table 8.

Table 8. Optimum characteristics of the extraction-spectrophotometric study for Fe(III).

Parameter	R_3	R_4
Color	Reddish brown	Reddish brown
The pH range under study	1-6	1-6
pH of maximum extraction	5	5
Organic solvent	Butanol-1	Butanol-1
Extraction time	3 min	3 min
λ_{max}, nm	490	490
Molar absorption coefficient, ε ($L \cdot mol^{-1} \cdot sm^{-1}$)	$6.1 \cdot 10^4$	$4.9 \cdot 10^3$
R,%	89.4	86
Beer's law interval, ($\mu g \cdot mL^{-1}$)	0.112-3.36	0.112-3.36
Correlation coefficient	0.975	0,99
Distribution coefficient	124	5
Extraction factor	50	50
Detection limit ($\mu g \cdot mL^{-1}$)	0.077	0,08

The results presented in the table demonstrate that reagents R_3 and R_4 form stable reddish-brown complexes with the component under study, the maximum extraction of which is achieved at pH 5 using butanol-1 as an organic solvent. For both reagents, the optimal extraction time is 3 minutes, and the light absorption maxima are observed at a wavelength of 490 nm. Reagent R_3 is characterized by a significantly higher molar absorption coefficient and distribution coefficient compared to R_4, which indicates greater sensitivity and extraction efficiency. The degree of complex recovery for R_3 is also higher and amounts to 89.4%, while for R_4 it is 86%. Both reagents obey Beer's law in the same concentration range of 0.112–3.36 μg/ml and have high correlation coefficients, confirming the linearity of the calibration curve. Low detection limits demonstrate the possibility of using the developed methods for determining trace amounts of the substance.

The ratios of the components in the resulting complex were determined using isomolar series methods, equilibrium shift methods, and the Starik-Barbanel relative yield method. The components are in a 1:2 ratio. Astakhov's method was used to determine the number of protons formed during complex formation and to substantiate the ratios of the corresponding components. It was found that the dependence of $\lg\left(\frac{\Delta A}{\Delta A_{lim}-\Delta A)}\right)$ on pH in the pH range of 4-5 has a slope of 2, and the complexing agent is in the form of $Fe(OH)_2^+$. This means that two protons are replaced during the reaction with the ligand. Using the least squares method, an equation corresponding to the calibration curve is calculated: $A = 0.176x+0.097$ for R_3 and $y = 0.148x + 0.032$ for R_4.

The effect of various ions on butanol-1 extraction was studied. The results are shown in Table 9.

Table 9. Effect of interfering ions on Fe(III) extraction.

Ions	Mass ratio of ions		Ions	Mass ratio of ions	
	R_3	R_4		R_3	R_4
Na(I)	2040	2000	Co(II)	2250	2000
K(I)	3010	3000	Cu(II)	480	450

Mg(II)	1500	1500	Pb(II)	2000	2000
Ca(II)	250	200	Sr(II)	750	800
Ba(II)	8700	8000	Al(III)	650	750
Zn(II)	3000	2500	Cr(III)	300	450
Cd(II)	5000	4500	Ti(IV)	460	410
Mn(II)	2590	2500	Mo(VI)	810	750
Ni(II)	2700	2800	W(VI)	450	400

The results showed that this technique is characterized by high selectivity. According to the data in Table 9, most of the studied ions have a minimal effect on the process of Fe(III) complexation with reagents R_3 and R_4. The ligands demonstrate the best stability towards the presence of foreign ions in the presence of Ba(II), Cd(II), K(I), Zn(II), Ni(II), and Mn(II). This is confirmed by the highest values of the permissible mass ratios for these ions. At the same time, Ca(II), Cr(III), Cu(II), Ti(IV), and W(VI) ions have the greatest interfering effect, which is characterized by relatively low permissible ratios. For most of the studied cations, the mass ratios calculated for R_3 and R_4 are close, which indicates their similar selectivity. Ligand R_3 exhibits somewhat greater stability towards the influence of individual ions, while ligand R_4 demonstrates better results for some other elements. The permissible mass ratios have wide limits, indicating the reagents' high selectivity for Fe(III). This means that even in the presence of significant concentrations of accompanying ions, the method is highly selective. Thus, the obtained results demonstrate the potential for the effective use of R_3 and R_4 ligands for the extraction preconcentration and determination of Fe(III) in complex samples with multicomponent compositions.

Application of the developed methods to various samples

The feasibility of using various synthetic sorbents, as well as extraction methods, to determine trace amounts of ferric iron ions in complex samples was investigated. The results for determining trace amounts of iron (III) in complex samples after preconcentration with sorbents S_1-S_{11} were compared with ICP-OES and are presented in Table 10.

Table 10. Determination of Fe(III) content in complex samples using sorbents S_1-S_{11} (n=5, P=0.95).

Objects	Sorbent	Reagent	$\bar{X} \pm \frac{t_{p.f.} \cdot S}{\sqrt{n}}$,	S_r
Buckwheat, %	S_4	R_1	$(0.358 \pm 0.013) \cdot 10^{-3}$	0,039
		ICP-OES	$(0.371 \pm 0.013) \cdot 10^{-3}$	0,043
	S_6	R_1	$(0.491 \pm 0.019) \cdot 10^{-3}$	0,028
		ICP-OES	$(0.499 \pm 0.018) \cdot 10^{-3}$	0,031
Red beans, %	S_5	R_1	$(0.774 \pm 0.027) \cdot 10^{-3}$	0,027
		ICP-OES	$(0.78 \pm 0.028) \cdot 10^{-3}$	0,031
	S_7	R_1	$(0.672 \pm 0.038) \cdot 10^{-3}$	0,049
		ICP-OES	$(0.679 \pm 0.039) \cdot 10^{-3}$	0,051
Spinach, %	S_{10}	R_1	$(0.299 \pm 0.01) \cdot 10^{-3}$	0,025
		ICP-OES	$(0.311 \pm 0.01) \cdot 10^{-3}$	0,029
	S_{11}	R_1	$(0.225 \pm 0.01) \cdot 10^{-3}$	0,032
		ICP-OES	$(0.236 \pm 0.01) \cdot 10^{-3}$	0,035
Mushrooms, %	S_{10}	R_1	$(0.127 \pm 0.01) \cdot 10^{-3}$	0,047
		ICP-OES	$(0.142 \pm 0.01) \cdot 10^{-3}$	0,051
	S_{11}	R_1	$(0.123 \pm 0.01) \cdot 10^{-3}$	0,041
		ICP-OES	$(0.132 \pm 0.01) \cdot 10^{-3}$	0,045
Corn, %	S_{10}	R_1	$(0.329 \pm 0.012) \cdot 10^{-3}$	0,031
		ICP-OES	$(0.341 \pm 0.013) \cdot 10^{-3}$	0,034
Broccoli, %	S_{11}	R_1	$(0.157 \pm 0.01) \cdot 10^{-3}$	0,039
		ICP-OES	$(0.168 \pm 0.01) \cdot 10^{-3}$	0,043
Drinking water, $mg \cdot L^{-1}$	S_2	R_1	$(0.772 \pm 0.032) \cdot 10^{-3}$	0,037
		ICP-OES	$(0.789 \pm 0.04) \cdot 10^{-3}$	0,044
	S_9	R_1	$(0.876 \pm 0.041) \cdot 10^{-3}$	0,041
		ICP-OES	$(0.887 \pm 0.048) \cdot 10^{-3}$	0,047
Sea water, $mg \cdot L^{-1}$	S_2	R_1	$(0.672 \pm 0.029) \cdot 10^{-3}$	0,037
		ICP-OES	$(0.691 \pm 0.033) \cdot 10^{-3}$	0,042
	S_9	R_1	$(0.716 \pm 0.025) \cdot 10^{-3}$	0,031
		ICP-OES	$(0.729 \pm 0.029) \cdot 10^{-3}$	0,035

The results presented in the table reflect the determination of the iron (III) content in various food and water samples using sorbents S_1–S_{11}. The obtained average concentration values are characterized by a high degree of reproducibility, as evidenced by the low relative standard deviation of S_r, confirming the high accuracy and reliability of the analytical method used. A comparison of the obtained results with ICP-OES demonstrates their good repeatability. Overall, the data in the table confirm the effectiveness of the studied sorbents and their potential for practical application in determining trace amounts of the iron (III) in food and water samples.

The results of the extraction-photometric analysis of iron(III) in complex samples are presented in Table 11 and compared with the ICP-OES analysis data.

Table 11. Determination of Fe(III) ions in various objects by the extraction-photometric method (n=5, P=0.95).

Objects	Reagent	$\bar{X} \pm \frac{t_{p.f.}S}{\sqrt{n}}$	S_r
Apple (Gyzylahmed)	R_1	$(0.549\pm0.036)\cdot10^{-3}$	0,057
	ICP-OES	$(0.561\pm0.041)\cdot10^{-3}$	0,063
Apple (Simirenko)	R_1	$(0.567\pm0.035)\cdot10^{-3}$	0.055
	ICP-OES	$(0.576\pm0.035)\cdot10^{-3}$	0.054
Feijoa, %	R_1	$(0.239\pm0.013)\cdot10^{-3}$	0,048
	R_3	$(0.237\pm0.014)\cdot10^{-3}$	0,051
	R_4	$(0.241\pm0.012)\cdot10^{-3}$	0,045
	ICP-OES	$(0.24\pm0.012)\cdot10^{-3}$	0,044
Spinach, %	R_1	$(0.578\pm0.029)\cdot10^{-3}$	0,044
	ICP-OES	$(0.586\pm0.032)\cdot10^{-3}$	0,048
Red beans, %	R_1	$(0.478\pm0.022)\cdot10^{-3}$	0,041
	R_3	$(0.451\pm0.025)\cdot10^{-3}$	0,049
	R_4	$(0.437\pm0.023)\cdot10^{-3}$	0,046
	ICP-OES	$(0.486\pm0.022)\cdot10^{-3}$	0,039
Mushrooms (Champignons)	R_1	$(0.341\pm0.014)\cdot10^{-3}$	0,037
	R_3	$(0.345\pm0.014)\cdot10^{-3}$	0,035
	R_4	$(0.349\pm0.016)\cdot10^{-3}$	0,041

	ICP-OES	$(0.353\pm0.017)\cdot10^{-3}$	0,044
Sea water, $mg\cdot L^{-1}$	R_1	$(0.199\pm0.005)\cdot10^{-3}$	0,021
	R_3	$(0.184\pm0.005)\cdot10^{-3}$	0,025
	ICP-OES	$(0.189\pm0.006)\cdot10^{-3}$	0,026

The presented results characterize the determination of the test component in food and water samples using reagents R_1, R_3, and R_4 and the ICP-OES method. The values obtained by the various methods are in good agreement with each other, confirming the reliability and accuracy of the analysis. Overall, the results demonstrate that these methods can be effectively used for analyzing of various samples, and the obtained data are comparable with the results of ICP-OES spectroscopy.

CONCLUSIONS

1. New preconcentration methods for determining trace amounts of iron(III) were developed. This study included a detailed examination and optimization of methods for the sorption and extraction preconcentration of iron(III) in its aqueous solutions and various complex samples.
2. To implement the sorption preconcentration of iron(III), sorbents based on a copolymer of maleic anhydride with styrene and various amines (S_1-S_9) were synthesized. Two of the resulting sorbents were additionally modified with reagent R_2 and S_{10} and S_{11}. Two new chemical reagents, R_3 and R_4, were synthesized and single crystals of these compounds were obtained.
3. The composition of the synthesized sorbents was studied using IR spectroscopy. The reagent-modified sorbents were also studied using SEM/EDS and UV/visible spectroscopy. The temperature stability of the sorbents was studied using thermal analysis methods. The composition and structure of the obtained reagents R_3 and R_4 were established by X-ray diffraction analysis.
4. The main sorption characteristics of the obtained sorbents during the sorption of iron(III) were studied, and the optimal conditions for the sorption process were established. Various models were

used to describe the sorption process, in particular, the Langmuir, Freundlich, and Dubinin-Radushkevich models. Sorption kinetics was investigated using pseudo-first-order and pseudo-second-order models. The desorption process with synthesized sorbents was studied, and the optimal eluent for removing iron(III) was determined. The established parameters ensure the possibility of efficient regeneration and reuse of the sorption material.

5. A method for the extraction preconcentration of Fe(III) using reagents R_1, R_3, and R_4 was developed. The main extraction parameters were established.
6. The effect of various foreign ions, in particular Na(I), K(I), Ca(II), Mg(II), Ni(II), Co(II), Mn(II), Zn(II), Cu(II), W(VI), and others, on the concentration of Fe(III) ions was studied; the limits of influence of certain ions on the studied processes were established. It was found that a multiple increase in the concentration of foreign ions does not affect the determination of Fe(III), indicating the high selectivity of the applied methods.
7. The developed methods for preconcentration of iron (III) were successfully tested for the analysis of its trace amounts in matrices of natural and industrial origin – in fruits (various varieties of apples, strawberries, apricots, etc.), in cereals (buckwheat, corn, beans), in drinking and sea water, etc.

The main results of the dissertation are reflected in the following publications.

1. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Studying the sorption of Fe(III) ions by chelate-forming synthetic sorbents // 1st International Science and Engineering Conference. Baku. - 2018, -p. 14-15.
2. Eyyubova, E.C., Əhmədova, K.D., Nağıyev, X.C., Çıraqov, F.M. Dəmirin (III) yeni sintetik sorbentlə sorbsiyasının tədqiqi // Ümummilli Lider Heydər Əliyevin anadan olmasının 95-ci ildönümünə həsr olunmuş doktorant, magistr və gənc tədqiqatçıların "Kimyanın Aktual Problemləri" XII Beynəlxalq Elmi Konfransının materialları. Bakı. - 2018, - s. 209-210.
3. Эюбова, Э.Дж., Нагиев, Х.Дж., Чырагов, Ф.М.

Спектрофотометрическое определение Fe(III) с 2,3,4-тригидрокси-4`-(4``-аминобензол)азобензолом // Ümummilli Lider Heydər Əliyevin anadan olmasının 95-ci ildönümünə həsr olunmuş doktorant, magistr və gənc tədqiqatçıların "Kimyanın Aktual Problemləri" XII Beynəlxalq Elmi Konfrasının materialları. Bakı. - 2018, - c. 258-259.

4. Эюбова, Э.Дж., Нагиев, Х.Дж., Чырагов, Ф.М. Изучение сорбции ионов Fe(III) хелатообразующим сорбентом на основании сополимера стирола с малеиновым ангидридом и N,N`-дифенилгуанидина // Химия, Химические технологии и экология: Наука, производство, образование. Тезисы докладов международной научно-практической конференции и школы молодых ученых, Махачкала, - 2018, - с. 45-46.
5. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption of Fe (III) ions on maleic anhydride styrene copolymer-N,N'-diphenylguanidine // Research Journal of Chemistry and Environment, - 2019, vol. 23, № 6, - p. 41-51.
6. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption study of Fe(III) ions by synthetic chelating sorbent // III International Scientific Conference of Young Researchers, Baku. - 2019, - p. 146-148.
7. Эюбова, Э.Дж., Ахмедли, К.А., Нагиев, Х.Дж., Чырагов, Ф.М. Сравнение сорбции ионов Fe(III) природным и синтетическим сорбентом // Ümummilli Lider Heydər Əliyevin anadan olmasının 96-cı ildönümünə həsr olunmuş doktorant, magistr və gənc tədqiqatçıların "Kimyanın Aktual Problemləri" XIII Beynəlxalq Elmi Konfrasının materialları, Bakı. - 2019, - c. 109.
8. Eyyubova, E.J. Nagiyev, Kh.J., Chiragov, F.M. Adsorption study of Fe (III) ions by synthetic adsorbent: adsorption isotherms // Journal of Baku Engineering University- Chemistry and biology, - 2019, vol. 3, № 2, - p. 87-94.
9. Eyyubova, E.C., Əhmədova, K.D. Dəmirin (III) yeni sintetik sorbentlə sorbsiyasının tədqiqi // Ümummilli Lider Heydər Əliyevin anadan olmasının 96-cı ildönümünə həsr olunmuş doktorant, magistr və gənc tədqiqatçıların "Kimyanın Aktual Problemləri" XIII Beynəlxalq Elmi Konfrasının materialları, Bakı. - 2019, - s. 108.

10. Эюбова, Э.Дж., Нагиев, Х.Дж., Чырагов, Ф.М. Разработка новой методики концентрирования Fe(III) для разделения его из объектов окружающей среды // XI Всероссийская конференция по анализу объектов окружающей среды с международным участием «Экоаналитика-2019», Пермь, - 2019, - с. 180.
11. Эюбова, Э.Дж., Магеррамов, А.М., Цинцадзе, Г.В., Нагиев, Х.Дж., Чырагов, Ф.М. Сорбционно-фотометрическое исследование ионов железа (III) // Международная научно-методическая конференция «Химия-достижения и перспективы», посвященная 85-летию академика Гиви Цинцадзе, Тбилиси, - 2019, - с. 118-119.
12. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption study of Fe(III) ions by masc-2-amino-4-nitrophenol // Azerbaijan Chemical Journal, - 2020, № 2, - p. 26-33.
13. Eyyubova, E.J. Adsorption of Fe (III) ions by synthetic polymer based adsorbent // New Materials, Compounds and Applications, - 2020, vol.4, №1, - p. 44-53.
14. Eyyubova, E.J., Nagiev, Kh.J. Ahmadov, E.I., Chyragov, F.M. Adsorption study of Fe(III) ions on modified adsorbent // 1st International Symposium on Recent Advances in Fundamental and Applied Sciences (ISFAS-2021), Turkey, 2021, p.97.
15. Eyyubova, E.J., Nasibova, V., Nagiyev, Kh.J., Chiragov, F.M. Extraction-Spectrophotometric determination of Fe^{3+} in drinking water // 6th International Turkic World Conference on Chemical Sciences and Technologies (İTWCCST), Baku, - 2022, - p. 62.
16. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption study of Fe(III) ions with polymeric modified adsorbent // International Conference: Modern Problems of Theoretical & Experimental Chemistry, Devoted to the 90th anniversary of Academician Rafiga Aliyeva, Baku, -2022, - p. 31-32.
17. Eyyubova, E.J. Adsorption of Fe (III) ions on modified adsorbent: adsorption isotherms / Esmira Eyyubova, Khalil Nagiyev, Sabit Mammadov [et al.] // Azerbaijan Chemical Journal, - 2022, № 4, - p. 33-42.
18. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption study of Fe (III) on modified adsorbent: adsorption isotherms and kinetics // Sorbtsionnye i khromatograficheskie protsessy, -2022, vol.

22, № 4, - p. 433-441.
19. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Adsorption of Fe(III) ions on amine modified adsorbent // International scientific conference. “Chemistry-achievements and perspectives” dedicated to the 90th anniversary of the birth of academician Givi Tsintsadze, Tbilisi, - 2023, -p. 71.
20. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Comparative adsorption study of Fe(III) ions onto modified adsorbents // International conference: Modern trends in physics, Baku, - 2023, - p. 123-124.
21. Eyyubova, E.J. Investigation of adsorption of Fe (III) ions by polymer adsorbent: adsorption isotherms and kinetics // Journal of Baku Engineering University- Chemistry and biology, - 2023, vol. 7, № 2, - p. 171-177.
22. Eyyubova, E.J. Nagiyev, Kh.J., Chiragov, F.M. Equilibrium and kinetic studies of sorption of Fe(III) ions on R-modified sorbent with CSMA // Sorbtsionnye i khromatograficheskie protsessy, - 2023, vol. 23, № 6, - p.1094-1102.
23. Eyyubova, E.J., Mirzali, S., Lakhijova, S., Chiragov, F.M. Modification of polymer adsorbent with 4-aminobenzenesulphonamide and its application for determination of Fe(III) ions in strawberries // “Neft kimyası və kimya texnologiyasında müasir yanaşmalar” mövzusunda Respublika elmi konfransının materialları. Bakı. - 2023, - p. 88-89.
24. Eyyubova, E.J. Synthesis, X-ray analysis, specific electric conductivity study and antioxidant activity of novel compound based on 3-(1-phenyl-2,3-dimethylpyrazolone-5)azopentadione-2,4 / Esmira Eyyubova, Famil Chiragov, Faik Musayev [et al.] // Journal of the Indian Chemical Society, , - 2024, vol.101, issue 12, - 101473.
25. Eyyubova, E.J., Nagiyev, Kh.J., Lakhijova, S., Chiragov, F.M. Adsorption study of Fe(III) ions on different adsorbents // Химическая наука и образование, проблемы и перспективы развития. Сборник научных статей по итогам международной конференции, Махачкала, - 2024, p.138-141.
26. Eyyubova, E.J., Nagiyev, Kh.J., Chiragov, F.M. Extractive-spectrophotometric determination of Fe(III) in red beans //

Материалы LXII отчетной научной конференции преподавателей и научных сотрудников ВГУИТ за 2023 год, Воронеж, - 2024, - p. 154.
27. Эюбова, Э.Дж., Маммадова, Ф., Нагиев, Х.Дж., Чырагов, Ф.М. Сравнительная сорбция ионов Fe(III) природным и синтетическим сорбентом. XX Международная конференция // Спектроскопия Координационных соединений, Кубань, - 2024, -с. 82.
28. Eyyubova, E.J., Maharramli, K., Nagiyev, Kh.J., Chiragov, F.M. Determination of microamount of Fe(III) ions in apple samples by extractive-spectrophometric technique // Kyiv Conference on Analytical Chemistry: Modern Trends, Kyiv, - 2024, -p. 11.
29. Eyyubova, E.J., Kurbanova, L., Nagiyev, Kh., Chyragov, F.M. Extraction-photometric determination of Fe(III) ions in fruits // Ümummilli Lider Heydər Əliyevin anadan olmasının 102 illiyinə həsr olunmuş doktorant, magistr və gənc tədqiqatçıların Kimya və Kimya texnologiyası mövzusunda IV Respublika Elmi Konfransı, Bakı, - 2025, -p. 155-156.
30. Eyyubova, E.J., Mammadova, F.O., Nagiyev, Kh.J., Hamidov, S.Z., Chyragov, F.M. Determination of Fe(III) microamounts in fruits // Ümummilli Lider Heydər Əliyevin anadan olmasının 102 illiyinə həsr olunmuş Dördüncü Sənaye İnqilabı Dövründə Elm və Texnologiyaların Mövcud Vəziyyəti və İnkişaf Perspektivləri Beynəlxalq Elmi-Praktik Konfransının materialları, Gəncə, - 2025, - p. 17-18.
31. Eyyubova, E., Salahov, T., Nagiyev, Kh., Chyragov, F. Extraction of Fe(III) ions by polymer based adsorbent // MacroFrontiers 2025: 3rd International Scientific Conference on Macromolecular Compounds, Baku, - 2025, -p. 138-139.
32. Eyyubova, E.J. Preconcentration-based approaches for trace-level determination of Fe(III) // 2nd International Conference: Modern Problems of Theoretical and Experimental Chemistry dedicated to the 120th anniversary of academician Yusif Mammadaliyev, Baku, - 2025, - p. 349-350.

The defense will be held on **13 November of 2026 at 11^{00}** at the meeting of the Dissertation Council FD 2.16 Supreme Attestation Commission under the President of the Republic of Azerbaijan operating Baku State University.

Address: AZ 1148, Baku city, Z. Khalilov street, 33.

The dissertation is accessible at the Scientific Library of Baku State University.

Electronic version of the abstract is available on the official website of Baku State University.

Abstract was sent to the required addresses on 09 october of 2026.

Signed for print: 02.10.2026.
Paper format: 60x84, 1/16
Volume: 36895
Number of hard copies: 20