

**ЖАРАТЫЛЫСТАНУ ЖӘНЕ ГЕОГРАФИЯ ҒЫЛЫМДАРЫНЫҢ ӨЗЕКТІ
МӘСЕЛЕЛЕРІ**
АКТУАЛЬНЫЕ ПРОБЛЕМЫ ЕСТЕСТВЕННЫХ И ГЕОГРАФИЧЕСКИХ НАУК
ACTUAL PROBLEMS OF NATURAL AND GEOGRAPHICAL SCIENCES

IRSTI 31.21.01

<https://doi.org/10.51889/3005-6217.2026.89.3.006>

S.Saryuisin ^{1*}, M. Yesibolati ², Zh. Korganbayeva ³

¹“D.V.Sokolsky Institute of Fuel, Catalysis and Electrochemistry” JSC, Almaty, Kazakhstan

²Technical University of Denmark, Kongens Lyngby, Denmark

³Abai Kazakh National Pedagogical University, Almaty, Kazakhstan.

*e-mail: Saryuisin.sn@gmail.com

**PREPARATION AND CHARACTERIZATION OF PECTIN–SILICA COMPOSITES
WITH MODIFIED SURFACE PROPERTIES**

Abstract

The aim of this study was to prepare and characterize pectin–silica composites with different surface properties and to evaluate the effect of silica surface modification on pectin immobilization. Unmodified silica (SiO₂) and APTES-functionalized silica (SiO₂–APTES) were used as inorganic components for the preparation of Pectin/SiO₂ and Pectin/SiO₂–APTES composites under comparable conditions. The immobilization of pectin was evaluated by viscometric analysis of the residual polymer concentration in the filtrate, while the structural and morphological characteristics of the obtained materials were investigated using Fourier-transform infrared spectroscopy (FTIR) and scanning electron microscopy (SEM). A pronounced difference in pectin immobilization efficiency was observed for the two silica surfaces. The immobilization efficiency of pectin on unmodified SiO₂ was 39.5%, whereas the use of APTES-functionalized silica increased the immobilization efficiency to 98.7%. FTIR analysis confirmed the coexistence of characteristic structural features of silica, APTES-derived organic groups, and pectin in the Pectin/SiO₂–APTES composite. Changes in the O–H, carboxyl, and C–H spectral regions indicated interactions between pectin functional groups and the modified silica surface. SEM observations revealed substantial morphological changes after pectin immobilization, with the resulting composite exhibiting a more heterogeneous and densely packed structure compared with the initial silica materials. The obtained results demonstrate that modification of silica surface properties can substantially improve pectin immobilization and influence the structural organization of pectin–silica composites. The prepared materials may be considered promising polymer–inorganic systems for further investigation in adsorption and related surface processes.

Keywords: pectin, silica, pectin–silica composite, surface modification, pectin immobilization, adsorption.

С.Н. Сарыүйсін^{1,*}, М.Н. Есиболати², Ж.Қ. Қорғанбаева³

¹“Д.В. Сокольский атындағы жсанармай, катализ және электрохимия институты” АҚ,
Алматы, Қазақстан

²Дания Техникалық университеті, Конгс-Люнгбю, Дания

³Абай атындағы Қазақ ұлттық педагогикалық университеті, Алматы, Қазақстан

*e-mail: Saryuisin.sn@gmail.com

БЕТКІ ҚАСИЕТТЕРІ МОДИФИКАЦИЯЛАНҒАН ПЕКТИН-СИЛИКАТТЫ КОМПОЗИТТЕРДІ АЛУ ЖӘНЕ СИПАТТАУ

Аңдатпа

Зерттеудің мақсаты беткі қасиеттері әртүрлі пектин-силикатты композиттерді алу және сипаттау, сондай-ақ кремний диоксиді бетінің модификациясының пектиннің иммобилизациялануына әсерін бағалау болды. Салыстырмалы жағдайларда Pectin/SiO₂ және Pectin/SiO₂-APTES композиттерін алу үшін модификацияланбаған кремний диоксиді (SiO₂) және APTES-пен функционалдандырылған кремний диоксиді (SiO₂-APTES) пайдаланылды. Пектиннің иммобилизациялану дәрежесі фильтраттағы полимердің қалдық концентрациясын вискозиметриялық әдіспен анықтау арқылы бағаланды. Алынған материалдардың құрылымдық және морфологиялық сипаттамалары Фурье түрлендіруімен инфрақызыл спектроскопия (FTIR) және сканерлеуші электрондық микроскопия (SEM) әдістерімен зерттелді. Кремний диоксидінің беткі қасиеттеріне байланысты пектиннің иммобилизациялану тиімділігінің айқын айырмашылығы анықталды. Модификацияланбаған SiO₂ бетінде пектиннің адсорбциялану тиімділігі 39,5% құраса, SiO₂-APTES қолдану иммобилизация тиімділігін 98,7%-ға дейін арттырды. FTIR-спектроскопия нәтижелері Pectin/SiO₂-APTES композитінде кремний диоксидіне, APTES-тен туындайтын органикалық топтарға және пектингіе тән құрылымдық белгілердің қатар болуын растады. О–Н, карбоксил және С–Н топтарына сәйкес спектрлік аймақтардағы өзгерістер пектиннің функционалдық топтары мен модификацияланған кремний диоксиді беті арасындағы өзара әрекеттесулерді көрсетті. SEM нәтижелері пектинді иммобилизациялау нәтижесінде бастапқы кремний құрамды материалдармен салыстырғанда композит бетінің морфологиясы айтарлықтай өзгеріп, неғұрлым біртекті емес және тығыз құрылым қалыптасқанын көрсетті. Алынған нәтижелер кремний диоксидінің беткі қасиеттерін модификациялау пектиннің иммобилизациялануын едәуір арттырып, пектин-силикатты композиттердің құрылымдық ұйымдасуына әсер ететінін көрсетті. Алынған материалдар сорбциялық және басқа да беттік процестерде әрі қарай зерттеуге перспективалы полимер-бейорганикалық жүйелер болып табылады.

Түйін сөздер: пектин, кремний диоксиді, пектин-силикатты композит, бетті модификациялау, пектиннің иммобилизациялануы, адсорбция.

Сарыүйсін С.Н.^{1,*}, Есиболати М. Н.², Қорғанбаева Ж.Қ.³

¹АО “Институт топлива, катализа и электрохимии им. Д.В.Сокольского”,
Алматы, Казахстан

²Датский технический университет, Конгс-Люнгбю, Дания

³Казахский национальный педагогический университет имени Абая, Алматы, Казахстан

*e-mail: Saryuisin.sn@gmail.com

ПОЛУЧЕНИЕ И ХАРАКТЕРИСТИКА ПЕКТИН-СИЛИКАТНЫХ КОМПОЗИТОВ С МОДИФИЦИРОВАННЫМИ ПОВЕРХНОСТНЫМИ СВОЙСТВАМИ

Аннотация

Целью настоящего исследования являлось получение и характеристика пектин-силикатных композитов с различными поверхностными свойствами, а также оценка влияния модификации поверхности диоксида кремния на иммобилизацию пектина. В качестве

неорганических компонентов для получения композитов Pectin/SiO₂ и Pectin/SiO₂-APTES использовали немодифицированный диоксид кремния (SiO₂) и функционализированный APTES диоксид кремния (SiO₂-APTES) при сопоставимых условиях. Степень иммобилизации пектина оценивали вискозиметрическим методом по остаточной концентрации полимера в фильтрате. Структурные и морфологические характеристики полученных материалов исследовали методами инфракрасной спектроскопии с преобразованием Фурье (FTIR) и сканирующей электронной микроскопии (SEM). Установлено существенное различие в эффективности иммобилизации пектина в зависимости от поверхностных свойств диоксида кремния. Эффективность адсорбции пектина на немодифицированном SiO₂ составила 39,5%, тогда как использование функционализированного SiO₂-APTES позволило повысить эффективность иммобилизации до 98,7%. По данным FTIR-спектроскопии в композите Pectin/SiO₂-APTES выявлено сочетание характерных структурных признаков диоксида кремния, органических групп APTES и пектина. Изменения в областях полос, соответствующих О-Н-, карбоксильным и С-Н-группам, указывают на взаимодействие функциональных групп пектина с модифицированной поверхностью диоксида кремния. По данным SEM после иммобилизации пектина наблюдались выраженные морфологические изменения, сопровождавшиеся формированием более неоднородной и плотной структуры композита по сравнению с исходными кремнийсодержащими материалами. Полученные результаты показывают, что модификация поверхностных свойств диоксида кремния позволяет существенно повысить иммобилизацию пектина и влияет на структурную организацию пектин-силикатных композитов. Полученные материалы представляют интерес как полимер-неорганические системы для дальнейшего исследования в сорбционных и других поверхностных процессах.

Ключевые слова: пектин, диоксид кремния, пектин-силикатный композит, модификация поверхности, иммобилизация пектина, адсорбция.

Introduction. Water pollution is a major global environmental challenge driven by population growth, economic development, urbanization, and increasing pressure on water resources [1]. Contamination of aquatic systems by industrial, agricultural, and domestic wastewater can adversely affect ecosystems, human health, and the availability of water resources [2]. According to the World Health Organization and UN-Water, approximately 42% of household wastewater generated globally in 2022 was not safely treated before discharge, corresponding to an estimated 113 billion m³ of wastewater released to the environment with inadequate or no treatment [3]. At the same time, monitoring of industrial wastewater treatment remains limited, indicating a substantial need for effective and accessible technologies for wastewater purification. Wastewater may contain a complex mixture of inorganic and organic contaminants, including heavy metal ions, dyes, nutrients, pharmaceuticals, pesticides, and other persistent or emerging pollutants [4, 5]. The diversity and chemical stability of these contaminants can make their removal challenging and may require the application or combination of different treatment processes. Conventional and advanced approaches include precipitation, coagulation–flocculation, ion exchange, membrane separation, biological treatment, electrochemical processes, advanced oxidation, and adsorption [6, 7]. The selection of a treatment method depends on the type and concentration of the contaminant, wastewater composition, required treatment efficiency, energy demand, and operating cost.

Among these technologies, adsorption has attracted considerable attention because of its operational simplicity, versatility, and effectiveness in removing a broad range of inorganic and organic contaminants from aqueous systems [8]. A wide range of adsorbents has been investigated, including activated carbon, zeolites, clays, biochar, carbon-based nanomaterials, and synthetic and natural polymeric materials [9]. However, the practical application of conventional adsorbents can be limited by production costs, regeneration requirements, or environmental considerations associated with their preparation and disposal [10]. Consequently, the development of alternative adsorbents from renewable and biodegradable resources has become an important direction in wastewater treatment research.

Biopolymers have emerged as promising materials for sustainable adsorbents because of their abundance, biodegradability, biocompatibility, and the presence of functional groups capable of

interacting with various pollutants [11]. Polysaccharides such as chitosan, cellulose, and alginate have been widely investigated for the removal of heavy metals, dyes, pharmaceuticals, and other contaminants from aqueous media [12, 13]. Their adsorption and structural properties can be enhanced through chemical modification, crosslinking, incorporation of inorganic phases, and formation of polymer–inorganic composites, enabling the development of hybrid materials with tailored surface properties.

Within the group of natural polysaccharides, pectin is of particular interest because it contains abundant hydroxyl and carboxyl groups that provide hydrophilic and functional sites for the development of hybrid materials [14]. Incorporation of an inorganic phase can further modify the structural and surface properties of pectin-based materials [15].

Silica (SiO_2) is a suitable inorganic component because of its high specific surface area, surface hydroxyl groups, chemical stability, and ability to undergo surface functionalization [16]. Combining silica with pectin can therefore provide organic–inorganic composites with tunable structural, surface, and adsorption properties. However, the interaction between polymer functional groups and the silica surface depends strongly on the surface chemistry of the inorganic phase.

The surface properties of silica can be further tailored through chemical functionalization to improve its interaction with polymer matrices [17, 18]. One effective strategy is the modification of silica with organosilanes, which are widely used to introduce additional functional groups onto the silica surface and to regulate the polymer–silica interface. Among various silane coupling agents, 3-aminopropyltriethoxysilane (APTES) is particularly attractive because its hydrolyzable ethoxy groups can participate in surface silanization, while the terminal aminopropyl group introduces additional functional sites capable of interacting with polymer functional groups [19]. Such surface modification may alter the interaction between silica and pectin and, consequently, affect the efficiency of polymer immobilization and the structure of the resulting composite.

Several studies have investigated pectin–silica hybrid materials and demonstrated their potential for adsorption and other functional applications. Krupska et al. [20] studied pectin/silica nanocomposites and showed that the incorporation of pectin affected their hydration and adsorption properties. Groult et al. [21] developed silica–pectin composite aerogels and demonstrated that the incorporation of silica modified their structural characteristics and specific surface area. Abouzeid et al. prepared pectin/silica-based hybrid materials and confirmed the formation of an organic–inorganic structure using spectroscopic and microscopic techniques. Boiko et al. investigated pectin immobilization in a polysiloxane matrix for Pb(II) removal and demonstrated the potential of such systems for adsorption applications. However, the effect of APTES functionalization of silica on pectin immobilization and composite formation remains insufficiently studied [22].

Therefore, the aim of this study was to prepare and characterize pectin–silica composites with different silica surface properties and to evaluate how surface modification affects pectin immobilization and the structural characteristics of the resulting composites [23]. Pectin/ SiO_2 and Pectin/ SiO_2 –APTES composites were prepared under comparable conditions, and the effect of silica surface modification was evaluated by viscometric determination of pectin immobilization efficiency, Fourier-transform infrared (FTIR) spectroscopy, and scanning electron microscopy (SEM).

Materials and methods.

1. Materials

Silica (SiO_2), 3-aminopropyltriethoxysilane (APTES), pectin (Pec, from apple, 50–75% esterification), hydrochloric acid were purchased from Sigma-Aldrich, St. Louis, MO, USA. Ethanol (reagent grade) was obtained from Talgar Alcohol LLP (Talgar, Kazakhstan). All reagents were used without further purification.

2. Preparation of SiO_2 –APTES

Silica (1.0 g) was dispersed in 30 mL of ethanol under magnetic stirring in a closed vessel for 10–15 min. Subsequently, 2.7 mL of APTES was added dropwise, and the suspension was stirred at room temperature for 3 h. The pH was then adjusted to 8.0, and the mixture was aged at room temperature for 12 h to promote hydrolysis and condensation of the silane groups. The resulting SiO_2 –APTES product was separated by filtration, washed three times with ethanol to remove

unreacted APTES and by-products, and dried at room temperature. Finally, the material was thermally treated at 110 °C for 30 min.

3. Preparation of the Pectin/SiO₂–APTES Composite

The Pectin/SiO₂–APTES composite was prepared by adsorption of pectin from an aqueous solution. First, 1.0 g of SiO₂–APTES was dispersed in 8.9 mL of distilled water under continuous stirring at room temperature. Then 11.1 mL of the 1 wt.% pectin solution was added to the SiO₂–APTES suspension, giving a total volume of 20 mL. The mixture was stirred at room temperature for 2 h and then kept in the mother liquor until complete settling of the composite. The precipitate was separated by filtration, washed with distilled water to remove unbound pectin, and dried at room temperature to constant weight.

4. Preparation of the Pectin/SiO₂ Composite

The Pectin/SiO₂ composite was prepared using the same procedure as described for Pectin/SiO₂–APTES, except that unmodified SiO₂ was used instead of SiO₂–APTES.

5. Characterization of the Composites by Physicochemical Methods

Viscosity measurements were carried out at 20°C using an Ubbelohde viscometer and a thermostatic bath (KRIO-VIS-E-01, Termex, Tomsk, Russia), and flow times were averaged over at least three measurements. Calibration curves were obtained from pectin solutions of known concentration prepared under identical conditions (same poly-mer batch, solvent).

Fourier Transform Infrared (FTIR) spectroscopy were obtained using a Nicolet iS5 from Thermo Scientific (Waltham, MA, USA), with a resolution of 3 cm^{–1} in the 4000–400 cm^{–1} region. Pellets for infrared analysis were obtained by grinding a mixture of 1mg sample with 100 mg dry KBr, followed by pressing the mixture into a mold.

Scanning electron microscopy (SEM) micrographs were obtained on a scanning elec-tron microscope JSM-6610 LV (“JEOL” Ltd., Tokyo, Japan) at an accelerating voltage of 15–20 kV.

Results.

Viscosity Analysis and Pectin Immobilization on the Silica Surface

The immobilization of pectin on the silica surface was evaluated indirectly by measuring the viscosity of the polymer solutions before and after the adsorption process. Since the viscosity of dilute pectin solutions depends on polymer concentration, the residual pectin concentration in the filtrate after composite preparation was determined using a previously established calibration curve relating specific viscosity (η_{sp}) to polymer concentration.

The amount of immobilized pectin was estimated from the difference between the initial and residual polymer concentrations, and the adsorption efficiency was calculated using equation. The obtained results are presented in (Table 1).

$$A = \frac{C_0 - C}{C_0} \times 100\%$$

Where A is the adsorption efficiency (%), C₀ is the initial pectin concentration, and C is the residual pectin concentration in the filtrate after adsorption.

Table 1. Pectin immobilization parameters for the prepared composites

Composite	Pectin content, wt.%		Adsorption efficiency, %
	Initial pectin concentration, wt.%	Residual pectin concentration, wt.%	
Pectin/SiO ₂	0.56	0.34	39.5±0.41
Pectin/SiO ₂ –APTES	0.56	0.01	98.7±0.12

As shown in Table 1, the adsorption efficiency of pectin strongly depended on the surface chemistry of silica. The unmodified SiO₂ exhibited a relatively low adsorption efficiency of 39.5%, indicating weak interactions between pectin macromolecules and the hydroxylated silica surface. In

contrast, APTES-functionalized silica demonstrated an adsorption efficiency of 98.7%, corresponding to almost complete immobilization of pectin under the selected preparation conditions.

The remarkable increase in pectin adsorption after APTES functionalization can be attributed to the introduction of aminopropyl groups onto the silica surface. These amino groups provide additional active sites capable of interacting with the hydroxyl and carboxyl groups of pectin through hydrogen bonding and electrostatic interactions, resulting in stronger polymer attachment and a significantly higher immobilization efficiency.

3.2. FTIR Spectroscopic Analysis

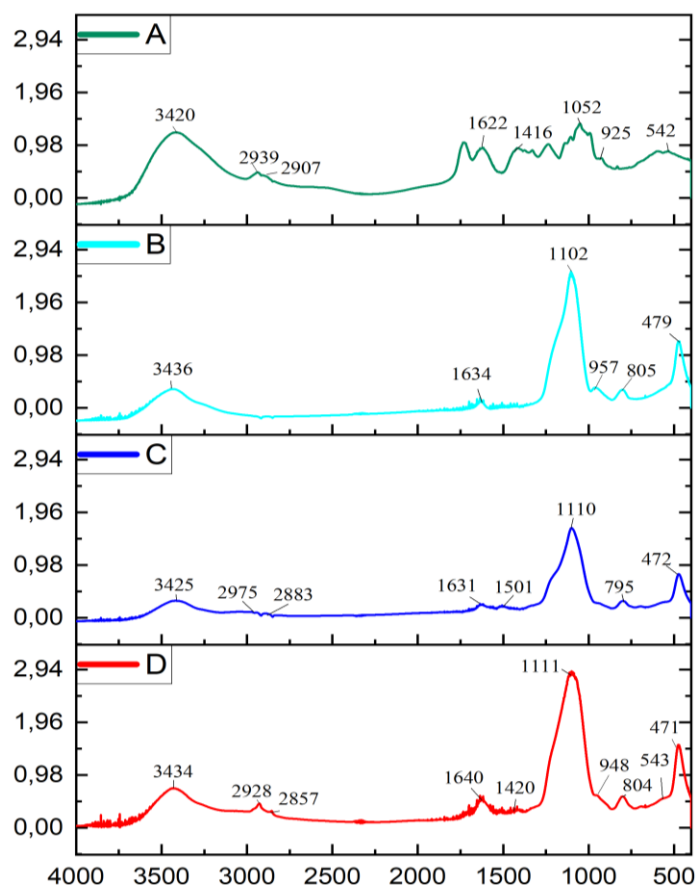


Figure 1. FTIR of (a) pectin, (b) SiO_2 , (c) SiO_2 -APTES, (d) Pec/ SiO_2 -APTES

Fourier-transform infrared (FTIR) spectroscopy was used to investigate the characteristic functional groups of pectin, silica, APTES-functionalized silica, and the resulting Pectin/ SiO_2 -APTES composite (Fig. 1). The FTIR spectrum of pectin (Fig. 1a) exhibited a broad band centered at 3420 cm^{-1} , which can be attributed to O–H stretching vibrations. The bands at 2939 and 2907 cm^{-1} were associated with C–H stretching vibrations of the polysaccharide backbone. The absorption band at 1622 cm^{-1} can be related to vibrations of carboxyl groups or adsorbed water, while the band at 1416 cm^{-1} is associated with vibrations of carboxylate groups. The region between 900 and 1200 cm^{-1} contained several bands characteristic of the polysaccharide structure. In particular, the band at 1052 cm^{-1} can be attributed to C–O and C–C stretching vibrations of the carbohydrate backbone. Similar characteristic pectin bands have been reported for pectin-based materials.

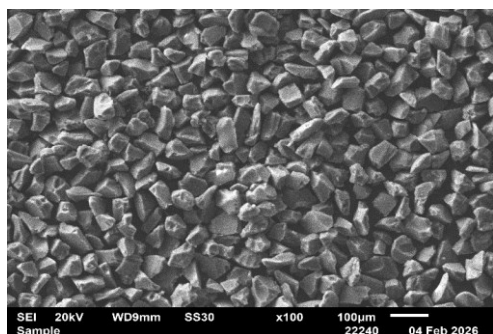
The spectrum of unmodified SiO_2 (Fig. 1b) was characterized by a broad absorption band at 3436 cm^{-1} and a band at 1634 cm^{-1} , corresponding mainly to O–H stretching and H–O–H bending vibrations, respectively, associated with surface hydroxyl groups and adsorbed water. The intense band at 1102 cm^{-1} was assigned to asymmetric stretching vibrations of the Si–O–Si framework.

Additional bands at 957 and 805 cm^{-1} can be attributed to surface Si–OH and Si–O–Si vibrations, respectively, while the band at 479 cm^{-1} corresponds to Si–O–Si bending vibrations. These features are characteristic of silica-based materials.

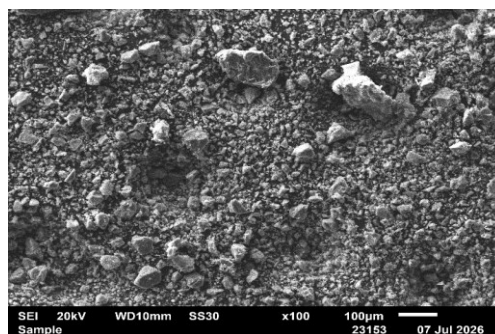
After functionalization with APTES, several changes were observed in the FTIR spectrum of SiO_2 –APTES (Fig. 1c). In particular, bands appeared at 2975 and 2883 cm^{-1} , which are characteristic of C–H stretching vibrations of the methylene groups in the aminopropyl chain of APTES. A band at 1501 cm^{-1} can be associated with vibrations of amino groups, although its assignment should be considered together with the other spectral changes. The strong band at 1110 cm^{-1} remained characteristic of the Si–O–Si network, while the bands at 795 and 472 cm^{-1} corresponded to Si–O–Si vibrations. The appearance of the C–H bands in the 2850–3000 cm^{-1} region provides evidence for the presence of APTES-derived organic groups on the silica surface.

The FTIR spectrum of the Pectin/ SiO_2 –APTES composite (Fig. 1d) combined characteristic features of both the polysaccharide and the silica-based matrix. The bands at 2928 and 2857 cm^{-1} were associated with C–H stretching vibrations. These bands may arise from overlapping contributions of the pectin polysaccharide backbone and the methylene groups of the APTES-derived aminopropyl chains. Therefore, their individual contributions cannot be unambiguously distinguished based solely on the FTIR spectra. The bands at 1640 and 1420 cm^{-1} can be related to vibrations of carboxyl-containing groups of pectin. At the same time, the strong absorption band at 1111 cm^{-1} and the bands at 804 and 471 cm^{-1} corresponded to the characteristic vibrations of the silica network. The presence of bands in the 2850–2950 cm^{-1} region together with the silica-related bands indicates the coexistence of organic and inorganic components in the composite.

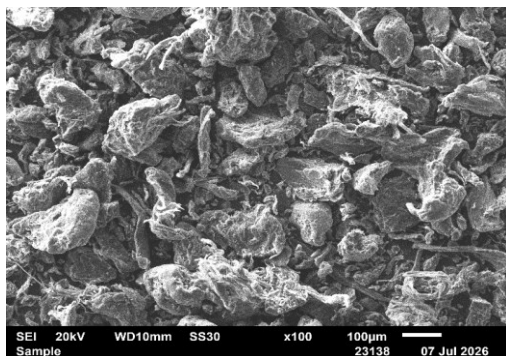
Discussion. Comparison of the spectra of SiO_2 –APTES and Pectin/ SiO_2 –APTES shows that the characteristic bands associated with pectin are retained after immobilization, while the dominant Si–O–Si absorption of the silica matrix remains present. The changes in the position and relative intensity of several bands, particularly in the O–H/carboxyl and C–H regions, indicate interactions between pectin functional groups and the functionalized silica surface. These spectral features are consistent with the high pectin immobilization efficiency determined by the viscometric analysis.



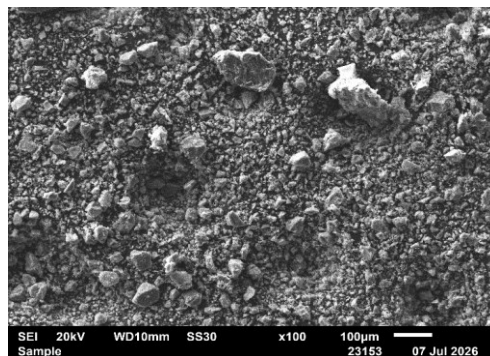
(a)



(b)



(c)



(d)

Figure 2. SEM microphotographs of (a) SiO₂, (b) Pec/SiO₂-APTES

The morphology of SiO₂ and the Pec/SiO₂-APTES composite was investigated by scanning electron microscopy (SEM), as shown in Figure 2. The SEM micrograph of the initial SiO₂ (Fig. 2a) reveals a relatively uniform particulate morphology composed predominantly of irregularly shaped particles with well-defined angular edges. The particles are distributed throughout the analyzed area and exhibit a comparatively compact arrangement. Individual particles remain clearly distinguishable, although partial aggregation and contact between neighboring particles can also be observed. The distinct particle boundaries and angular morphology are characteristic features of the initial silica surface under the applied imaging conditions.

A pronounced change in morphology is observed for the Pec/SiO₂-APTES composite (Fig. 2b). In contrast to the clearly defined particles of the initial SiO₂, the composite exhibits a substantially more heterogeneous and less ordered surface. The sharp angular contours of the silica particles become less distinguishable, while the surface contains irregular agglomerates and a finer particulate fraction distributed throughout the analyzed region. The material also appears more compact and structurally heterogeneous compared with the initial silica. These morphological changes indicate modification of the silica surface following APTES functionalization and subsequent pectin immobilization.

The reduced visibility of the original silica particle boundaries and the formation of irregular surface regions may be associated with the presence of an organic component on the silica surface and with aggregation occurring during composite preparation and drying. However, SEM observations alone cannot establish the chemical nature of the surface interactions or distinguish conclusively between physical deposition and specific interactions of pectin with the APTES-functionalized silica. Therefore, the morphological observations should be considered together with the results obtained by complementary characterization methods.

In particular, the SEM results are consistent with the viscometric analysis, which demonstrated a pectin adsorption efficiency of 98.7% for the Pec/SiO₂-APTES system. The substantial decrease in the residual pectin concentration after contact with APTES-functionalized silica indicates extensive immobilization of the polymer. Together with the FTIR results showing the presence of characteristic pectin- and silica-related functional groups, the observed morphological transformation supports the successful incorporation of pectin into the silica-based composite. Thus, SEM provides additional morphological evidence for the formation of Pec/SiO₂-APTES, complementing the quantitative adsorption and spectroscopic data.

Conclusion. In this study, pectin-silica composites with different silica surface properties were prepared and characterized using viscometric analysis, FTIR spectroscopy, and SEM. Pectin/SiO₂ and Pectin/SiO₂-APTES composites were obtained under comparable conditions to evaluate the effect of silica surface modification on pectin immobilization and composite structure.

The viscometric analysis demonstrated a pronounced difference in pectin immobilization depending on the silica surface chemistry. The immobilization efficiency of pectin on unmodified SiO₂ was 39.5%, whereas the use of APTES-functionalized silica increased the immobilization efficiency to 98.7%. This result indicates that modification of the silica surface with aminopropyl groups substantially enhanced the interaction between silica and pectin under the selected experimental conditions.

FTIR analysis confirmed the presence of characteristic bands associated with silica, APTES-derived organic groups, and pectin in the Pectin/SiO₂-APTES composite. The appearance of C-H stretching bands associated with the aminopropyl groups after silica functionalization, together with changes in the spectral features of the composite, supports the immobilization of pectin on the functionalized silica surface. SEM observations further revealed pronounced morphological changes after pectin immobilization, with the composite exhibiting a more heterogeneous and densely packed structure compared with the initial SiO₂ and SiO₂-APTES materials.

Overall, the results demonstrate that modification of silica surface properties can substantially improve pectin immobilization and influence the morphology of the resulting polymer-silica

composite. The obtained Pectin/SiO₂-APTES material provides a basis for further investigation of pectin-silica composites in adsorption and related surface processes.

Financing: This research was conducted as part of the targeted funding program for the project AP23489662, titled “Investigation of the interaction of Ni²⁺ and Co²⁺ ions with organic ligands to assess the feasibility of chromatographic separation of metal ions.”

Acknowledgments: The research undertaken was made possible by the equal scientific involvement of all the authors concerned.

Author Contributions: Conceptualization: Talgatov E., Korganbayeva Zh., Formal analysis: Talgatov E., Investigation: Zamanbekova A., Methodology and Supervision: Saryuisin S., Yesibolati M., Writing – original draft: Saryuisin S., Writing – review & editing: Saryuisin S., Korganbayeva Zh.

Conflict of interest: The authors declare no conflict of interest. Data availability statement: The data presented in this study may be obtained on request from the corresponding author.

References:

1. Stokal M., Kroeze C. *Water, society and pollution in an urbanizing world: recent developments and future challenges // Current Opinion in Environmental Sustainability.* – 2020. – Vol. 46. – P. 11–15. – DOI: <https://doi.org/10.1016/j.cosust.2020.10.003>.
2. Shekhar C., Khosya R., Sharma A.K., Thakur K., Mahajan D., Kumar R., Kumar S., Sharma A.K. *A systematic review on health risks of water pollutants: classification, effects and innovative solutions for conservation // Toxicology Research.* – 2025. – Vol. 14, No. 1. – Article tfaf014. – DOI: <https://doi.org/10.1093/toxres/tfaf014>.
3. World Health Organization. *Progress on the proportion of domestic and industrial wastewater flows safely treated: mid-term status of SDG indicator 6.3.1 and acceleration needs, with a special focus on climate change, wastewater reuse and health.* Geneva: World Health Organization; 2024. – 101 p. – ISBN: 978-92-4-009908-1.
4. Khan A.U., Khan A.N., Waris A., Ilyas M., Zamel D. *Phytoremediation of pollutants from wastewater: A concise review // Open Life Sciences.* – 2022. – Vol. 17, No. 1. – P. 488–496. – DOI: <https://doi.org/10.1515/biol-2022-0056>.
5. Margot J., Rossi L., Barry D.A., Holliger C. *A review of the fate of micropollutants in wastewater treatment plants // WIREs Water.* – 2015. – Vol. 2, No. 5. – P. 457–487. – DOI: <https://doi.org/10.1002/wat2.1090>.
6. Kato S., Kansha Y. *Comprehensive review of industrial wastewater treatment techniques // Environmental Science and Pollution Research.* – 2024. – Vol. 31, No. 39. – P. 51064–51097. – DOI: <https://doi.org/10.1007/s11356-024-34584-0>.
7. Fei Y., Hu Y.H. *Recent progress in removal of heavy metals from wastewater: A comprehensive review // Chemosphere.* – 2023. – Vol. 135, No. 2. – P. 64–70. DOI: <https://doi.org/10.1016/j.chemosphere.2023.139077>.
8. Satyam S., Patra S. *Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review // Heliyon.* – 2024. – Vol. 17, No. 1. – P. 153–178. – DOI: <https://doi.org/10.1016/j.heliyon.2024.e29573>.
9. Sahu D., Pervez S., Karbhal I., Tamrakar A., Mishra A., Verma S.R., Deb M.K., Ghosh K.K., Pervez Y.F., Shrivastava K., Satnam M.L. *Applications of different adsorbent materials for the removal of organic and inorganic contaminants from water and wastewater – A review // Desalination and Water Treatment.* – 2024. – Vol. 48. P. 4791–4822. – DOI: 10.1016/j.dwt.2024.100253.
10. Baskar A.V., Muthamilselvi P., Karthikeyan R., et al. *Recovery, regeneration and sustainable management of spent adsorbents from wastewater treatment streams: A review // Science of the Total Environment.* – 2022. – Vol. 822. – P. 153–555. – DOI: 10.1016/j.scitotenv.2022.153555.

11. Crini G., Lichtfouse E. *Advantages and disadvantages of techniques used for wastewater treatment* // *Environmental Chemistry Letters*. – 2019. – Vol. 17. – P. 145–155. – DOI: <https://doi.org/10.1007/s10311-018-0785-9>.
12. Doyo A.N., Kumar R., Barakat M.A. *Recent advances in cellulose, chitosan, and alginate based biopolymeric composites for adsorption of heavy metals from wastewater* // *Journal of the Taiwan Institute of Chemical Engineers*. – 2023. – Vol. 151. – P. 105 - 195. – DOI: [10.1016/j.jtice.2023.105095](https://doi.org/10.1016/j.jtice.2023.105095).
13. Kaur K., Anmol. *Recent Advances in Chitosan-Based Adsorbents for Waste Water Management: A Review* // *ChemistrySelect*. – 2026. – Vol. 11, No. 9. – P. 728 - 941. – DOI: [10.1002/slct.72841](https://doi.org/10.1002/slct.72841).
14. Monfregola L., Leone M., Vittoria V., Amodeo P., Luca S. *Chemical modification of pectin: environmental friendly process for new potential material development* // *Polymer Chemistry*. – 2011. – Vol. 2. – P. 800. – DOI: <https://doi.org/10.1039/C0PY00341G>.
15. Li D.-Q., Li J., Dong H.-L., Li X., Zhang J.-Q., Ramaswamy S., Xu F. *Pectin in biomedical and drug delivery applications: A review* // *International Journal of Biological Macromolecules*. – 2021. – Vol. 185. – P. 49–65. – DOI: [10.1016/j.ijbiomac.2021.06.088](https://doi.org/10.1016/j.ijbiomac.2021.06.088).
16. Singh P., Srivastava S., Singh S.K. *Nanosilica: Recent Progress in Synthesis, Functionalization, Biocompatibility, and Biomedical Applications* // *ACS Biomaterials Science & Engineering*. – 2019. – Vol. 5, No. 10. – P. 4882–4898. – DOI: [10.1021/acsbiomaterials.9b00464](https://doi.org/10.1021/acsbiomaterials.9b00464).
17. Cashin V.B., Eldridge D.S., Yu A., Zhao D. *Surface functionalization and manipulation of mesoporous silica adsorbents for improved removal of pollutants: a review* // *Environmental Science: Water Research & Technology*. – 2018. – Vol. 4, No. 2. – P. 110–128. – DOI: [10.1039/C7EW00322F](https://doi.org/10.1039/C7EW00322F).
18. Li H., Cheng B., Gao W., Feng C., Huang C., Liu Y., Lu P., Zhao H. *Recent research progress and advanced applications of silica/polymer nanocomposites* // *Nanotechnology Reviews*. – 2022. – Vol. 11, No. 1. – P. 2928–2964. – DOI: <https://doi.org/10.1515/ntrev-2022-0484>.
19. Sypabekova M., Hagemann A., Rho D., Kim S. *Review: 3-Aminopropyltriethoxysilane (APTES) Deposition Methods on Oxide Surfaces in Solution and Vapor Phases for Biosensing Applications* // *Biosensors*. – 2023. – Vol. 13, No. 1. – P. 36. – DOI: [10.3390/bios13010036](https://doi.org/10.3390/bios13010036).
20. Krupska T.V., Klymenko N.Yu., Wei Q., Zheng J., Yang W., Turov V.V. *Nanocomposite systems pectin/silica and their properties* // *Chemistry, Physics and Technology of Surface*. – 2025. – Vol. 16, No. 3. – P. 311–321. – DOI: [10.15407/hftp16.03.311](https://doi.org/10.15407/hftp16.03.311).
21. Groult S., Buwalda S., Budtova T. *Tuning bio-aerogel properties. Part 3: Exploring silica-pectin composite aerogels for drug delivery* // *Biomaterials Advances*. – 2024. – Vol. 163. – P. 2105 - 2139. – DOI: <https://doi.org/10.1016/j.bioadv.2024.213954>.
22. Abouzeid R.E., Abd El-Kader A.H., Salama A., Fahmy T.Y.A., El-Sakhawy M. *Preparation and properties of novel biocompatible pectin/silica calcium phosphate hybrids* // *Cellulose Chemistry and Technology*. – 2022. – Vol. 56, No. 3–4. – P. 371–378. – DOI: <https://doi.org/10.35812/CelluloseChemTechnol.2022.56.33>.
23. Boiko Y., Kyshkarova V., Tomina V., Vaclavikova M., Melnyk I. *Harnessing diverse pectin fixation strategies in a polysiloxane matrix for the effective removal of lead(II) ions from aqueous media* // *Journal of Water Process Engineering*. – 2025. – Vol. 79. – P. 108 - 136. – DOI: [10.1016/j.jwpe.2025.108876](https://doi.org/10.1016/j.jwpe.2025.108876).