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CREATION OF SUSTAINABLE SORPTION MATERIALS FROM SECONDARY RESOURCES FOR THE PURIFICATION OF POLLUTED SOILS

Annotation. The development of effective sorbents for the purification of soils contaminated with heavy metals based on secondary resources is an urgent task of environmental safety of the Republic of Kazakhstan. Of particular interest in this area is the use of spent gas mask filters, the disposal of which allows us to simultaneously solve the problems of accumulation of hazardous waste and remediation of contaminated areas. In this work, the possibility of obtaining highly effective sorbents from spent gas mask filters for the extraction of Pb^{2+} Cd^{2+} and Cu^{2+} ions from polluted media is investigated. The sorbents were obtained by combined thermal and chemical modification of the starting material. The physicochemical properties of the developed materials were studied using low-temperature nitrogen adsorption BET analysis and IR Fourier spectroscopy. It was found that the modification leads to a significant increase in the specific surface area of sorbents (from 200 to 610 m^2/g), an increase in the total pore volume and the formation of oxygen-containing functional groups on the surface. Experimental studies of sorption have shown the high efficiency of the developed materials in relation to heavy metal ions. The maximum sorption capacity was 89 mg/g for Pb^{2+}, 53 mg/g for Cd^{2+} and 40 mg/g for Cu^{2+} with a removal efficiency of up to 92%. Kinetic analysis showed that the sorption process quickly reaches equilibrium within 12-24 hours and is best described by a pseudo-second-order model (R^2 0.97-0.99), which indicates the predominance of chemo sorption mechanisms. The results obtained confirm the prospects of using modified spent filters of gas masks for cleaning soils and water systems from heavy metals.

Keywords: sorbents, heavy metals, soil purification, used gas mask filters, surface modification, sorption tank.

Introduction

Soil pollution is currently one of the key global environmental threats that have arisen as a result of increased anthropogenic impact on natural systems. According to current estimates, more than a third of the planet`s soil cover has been polluted and degraded, covering about 2,1 billion hectares of land. This problem has a significant impact on food security, public health, and the sustainability of biogeochemical processes. As a result of the active use of pesticides, mineral fertilizers, and the development of industrial production, more than 20% of irrigated agricultural land in the world is contaminated with heavy metals such as lead, cadmium, arsenic, chromium, and other elements, concentrations of which often exceed acceptable environmental standards [1-3]. The generalization of international research data indicates that the presence of toxic metals in soils leads not only to a decrease in their fertility

and crop yields, but also to the accumulation of dangerous compounds in trophic chains, which poses serious risks to human health and ecosystem functioning.

This study focuses on solving an urgent environmental and chemical and chemical problem related to soil contamination with toxic substances and the parallel accumulation of hazardous man-made waste, in particular spent gas mask filters. Given the limitations of existing remediation methods, the high cost of commercial sorbents and the need to implement the principles of sustainable development, it seems reasonable to create new sorption materials based on secondary resources. The use of spent gas mask filters as a feedstock not only reduces the environmental burden due to their disposal, but also makes it possible to obtain promising materials with a developed porous structure and potentially high sorption capacity. The purpose of this work is to develop sorbents for the purification of contaminated soils based on these filters, as well as their physico-chemical study, including analysis of the structure, surface characteristics and mechanisms of sorption of toxic pollutants, which will assess the effectiveness and practical applicability of the created materials in soil purification technologies.

Current scientific evidence suggests that between 14 and 17% of arable land on the planet contains toxic metals in concentrations exceeding acceptable safe levels. In absolute terms, this corresponds to approximately 242 million hectares of agricultural land. Between 900 million and 1,4 billion people live within these territories, which clearly reflects the severity of the impact of soil pollution on public health and sustainable development processes. An additional concern is the accumulation of petroleum products and organic pollutants in soils, especially in regions associated with the extraction, progressing and transportation of hydrocarbons. Under such conditions, oil and its derivatives can persist in the soil environment for a long time, disrupting its physico-chemical characteristics and biological activity. Therefore, soil pollution is a complex multifactorial problem formed by both industrial and agricultural sources, which necessitates the development and implementation of effective methods for monitoring, analyzing and remediating soils [4-7].

Scientific papers devoted to soil remediation in the 21st century attest to the growing interest of the research community in the problem of eliminating soil pollution. Bibliometric studies record a steady increase in the number of publications examining the condition of polluted soils and ways to restore them. At the same time, China, the United States of America and European countries occupy leading positions in terms of the volume of scientific research in the field. The key research areas cover biological methods, including phytostabilization and bioremediation, physico-chemical technologies such as soil washing and stabilization, as well as the creation of innovative materials and technological solutions aimed at improving the efficiency of detoxification processes. However, most of the existing approaches are characterized by a number of limitations, including significant financial costs, duration of implementation, and limited applicability to various types of pollutants.

Sorption methods based on the selective binding of polluting components with solid sorbents are playing an increasingly prominent role among the relevant strategies for eliminating pollutants. These technologies make it possible to efficiently extract heavy metals and organic compounds from complex soil systems [8-10]. Materials based on activated carbons, zeolites, metal oxides, and biochar have high sorption efficiency, but their large-scale implementation is limited by economic and environmental aspects, which necessitates the search for more affordable starting materials and improved methods for their production [11-13]. There is also considerable interest in the problems of soil pollution and technologies for its elimination in domestic scientific publications. Thus, regional studies conducted in the

country indicate the widespread occurrence of heavy metal pollution near industrial agglomerations, which necessitates the formation of adapted monitoring systems and the development of local remediation measures. For Kazakhstan, where the oil and gas industry and the agricultural sector are intensively developed, soil pollution with petroleum products and metals is an important environmental and economic problem. This is confirmed by the results of a number of regional ecological and geochemical studies reflecting the relevance of this topic. At the same time, the number of domestic works devoted to the creation and implementation of innovative sorption materials for soil purification remains limited in comparison with foreign research.

This situation points to the existing scientific and practical gap and underlines the need to intensify research in the development of effective sorbents [14-20]. A characteristic feature of modern scientific approaches is the focus on the use of waste and secondary resources as raw materials for the production of sorption materials, which corresponds to the concepts of sustainable development and circular economy [21-24]. In particular, the disposal of technical waste, including used gas mask filters, makes it possible to simultaneously reduce the volume of hazardous waste and obtain functional sorbents with a high specific surface area and a developed porous structure. These characteristics are crucial for effective binding of target pollutants, including heavy metals and organic substances. Despite the existence of separate studies in related fields, comprehensive laboratory and applied work aimed at the physico-chemical substantiation and optimization of such materials is still underrepresented and requires further development, which determines the relevance and prospects of the chosen topic for modern research.

Research materials and methods

Spent gas mask filters from industrial and laboratory sources were used as raw materials for the manufacture of sorbents. The filters contain activated carbon6 fibrous fillers and binding materials, which makes them promising for producing sorbents with high porosity. To assess the sorption characteristics, soils contaminated with heavy metals (Pb^{2+}, Cd^{2+} and Cu^{2+}) and organic substances sampled in agricultural and industrial territories of the Republic of Kazakhstan were used. The concentrations of pollutants in soils were determined taking into account the maximum permissible values according to sanitary standards and GOST standards: Pb- 32 mg/kg, Cd-2.5 mg/kg, petroleum products -100 mg/kg. solution of high purity heavy metal salts ($Pb(NO_3)_2$, Cd $(NO_3)_2$ were used for chemical treatment of sorbents ×4H_2O, $CuSO_4$ 5H_2O) acids and bases (HCl, HNO_3, NaOH) for pH regulation, as well as deionized water. All chemicals used met the requirements of GOST 17319-2019 and GOST 17.4.4.02-2017 [25-26]. The physico-chemical study of the developed sorbents was carried out using a modern set of laboratory methods that make it possible to evaluate the morphology, surface structure, specific surface area and porosity of materials, as well as their chemical properties. The morphological features and microstructure of the sorbents were analyzed using a scanning electron microscope JSM-6510LV, which made it possible to visualize the particle shape, pore size, and degree of aggregation of carbon components. An infrared spectrophotometer Bruker Alpha was used to identify functional groups on the surface, which was used to determine chemical bonds and potential active centers involved in sorption processes. The specific surface area and porosity of the materials were determined by the nitrogen adsorption method Quantachrome Nova 1200e, which made it possible to evaluate their potential sorption capacity. The value of the zero charge point and the control of sorption conditions were carried out using a pH meter Hanna HI 2211, and the quantitative analysis of heavy metals in solutions and soils was carried out using atomic absorption spectrometry

Perkin Elmer Analyst 400, which ensures high accuracy and sensitivity of measurements. The use of this set of instrumental methods made it possible to comprehensively characterize the physico-chemical properties of the obtained sorbents and evaluate their effectiveness for cleaning contaminated soils.

The initial filters of the gas masks underwent mechanical processing, including grinding to particles 0,5-2 mm in size, subsequent thermal activation at 400-600 ^{0}C in an atmosphere of inert gas (nitrogen) and, if necessary, chemical modification using acids or bases to change the surface change. After treatment, the sorbents were washed with deionized water until a neutral pH was reached and dried at 105 ^{0}C to a constant weight.

To study the sorption of heavy metals, the static saturation methods was used: 0,5-1 g of sorbent was placed in a flask with 50 ml of a metal solution of a given concentration (10-100 mg/l) and kept at a constant temperature (25+-2 ^{0}C) and stirring at a speed of 200 rpm for 24 hours. After filtration, the residual metal concentration was determined by atomic absorption spectrometry (AAS). The sorption capacity of the material was calculated using the standard formula:

$$q_e = \frac{(C_0 - C_e)\,V}{m} \quad (1)$$

where: qe -amount of sorbed substance (mg/g), C_0 and C_e -initial and equilibrium metal concentration (mg/l), V- solution (l), m -sorbent weight.

The concentrations of pollutants in soils and the sorption efficiency were determined taking into account the maximum permissible concentrations and sanitary standards (San PiN 2.1.7.1322-03) [27], which ensured a correct comparison of the results with the permissible levels of pollution. The measurement accuracy was monitored using standard samples and repeated determinations (at least three parallel experiments for each variant). All experiments were performed in three repetitions, and the data obtained were statistically processed using standard methods for estimating errors and coefficients of variation, which made it possible to evaluate the reliability of the results and reproducibility of the methodology. The study of sorption kinetics was carried out at a fixed initial concentration of the contaminant with varying contact time in the range from 5 to 1440 minutes. The experimental data obtained were processed using kinetic models of the pseudo-first and pseudo-second orders, which made it possible to estimate the speed of the process and the nateru of the interaction of pollutants with the active centers of sorbents. The most adequate model was determined based on the correlation coefficients and the correspondence of the calculated values to the experimental data. To describe the equilibrium characteristics of sorption and estimate the maximum sorption capacity, experimental data were analyzed using Langmuir and Freundlich isotherms. The Langmuir model was used to estimate monomolecular sorption on an energetically homogeneous surface and was described by the equation:

$$q_e = \frac{q_{max}\,K_L\,C_e}{1 + K_L\,C_e} \quad (2)$$

where: q_{max}- maximum sorption capacity, mg/g, K_L-langmuir's constant, wich characterizes the sorption energy. The Freundlich model was used to describe sorption on an energetically inhomogeneous surfas and was expressed by the equation:

$$q_e = K_F\,C_e^{1/n} \quad (3)$$

where: K_F and n are empirical constants reflecting sorption capacity and sorption intensity, respectively. The choice of these models is due to their wide applicability for the analysis of heavy metal sorption by carbon-containing and modified materials.

Research results

Soil pollution with heavy metals is one of the most acute environmental problems in the

Republic of Kazakhstan, due to the high concentration of mining, metallurgical, chemical and energy enterprises. As a result of prolonged anthropogenic stress, lead, cadmium, copper and other toxic metal ions accumulate in the soils of industrial and adjacent territories, which are characterized by high resistance, bioaccumulation and the ability to migrate along trophic chains. This leads to degradation of the soil cover, a decrease in agricultural productivity and an increase in environmental risks to public health. A particular danger is that heavy metals practically do not decompose in natural conditions, and their removal from soils requires the of effective and economically sound technologies. In recent years, considerable attention has been paid to sorption purification methods as one of the most promising areas of remediation of contaminated soils and water systems. The effectiveness of such methods is largely determined by the properties of the sorbents used, primarily their specific surface area, porous structure, and the presence of functional groups capable of forming strong complexes with metal ions. At the same time, the industrial production of highly effective sorbents, such as activated carbons, is associated with significant energy and economic costs, which limits their widespread use in environmental rehabilitation.

In this context, the development of sorbents based on secondary resources, in particular spent gas mask filters, which contain carbon-containing materials with a potentially developed porous structure, is of particular interest. The annual accumulation of significant amounts of such weste in the Republic of Kazakhstan creates not only an environmental burden,but also pererequisites for their recycling and disposal to obtain functional materiales. Modification of spent gas mask filters by thermal and chemical treatment makes it possible to purposefully change their physico-chemical properties, from mico- and mesoprous structures introduce active functional groups,which makes them promising sorbents for binding heavy metals.Thus, the conducted research is aimed at scientific substantiation of the possibilty of recycling spent gas mask filters to obtain effective sorption materials for cleaning media contaminated with heavy metal ions. The results presented below and their discussion make it possible to assess the impact of the selected modification methods on the structure, chemical nature of the surface and sorption properties of the developed sorbents, as well as to confirm their practical applicability for solving urgent environmental problems in the Republic of Kazakhstan.

As a result of the experimental studies, sorbents based on spent gas mask filters were obtained, characterized by a developed porous structure and the presence of functionally active groups on the surface the physico -chemical characterization of the obtained sorbents has shown that various processing methods significantly change their structure and chemical properties. The table 1 shows data on specific surface area, porosity, functional groups, and zero charge point (pH_pzc)for the initial, heat- treated, and chemically modified sorbent.

Table 1- Physico-chemical characteristics of sorbents

№	Parameter	The original filter	Heat treated	Modified sorbent
1	Specific surface area, m^2/g	200	410	580
2	Pore volume, cm^3/g	0.20	0.42	0.55
3	Micropores,%	35	50	62
4	Mesopores, %	65	50	38
5	Average pore size,nm	3,2	4,1	4,8
6	pH_pzc	6,1	6,3	6,5
7	Availability of functional groups	-OH, C-H	-OH, C=O	-OH, C=O, -COOH
8	Ash content,%	12	10	9

As can be seen from the table, combined thermal and chemical treatment contributes to a significant increase in the specific surface area and pore volume, as well as the formation of

active functional groups, which positively affects the sorption capacity of materials. A decrease in ash content indicates the removal of mineral impurities, improving the purity of the carbon matrix.

To evaluate the effectiveness of sorbents, experiments were conducted to extract Pb^{2+}, Cd^{2+} and Cu^{2+} from model solutions at various initial concentrations. The table 2 shows the values of sorption capacity Qe, removal efficiency, time to reach equilibrium, optimal pH, and kinetic constants.

Table 2-Sorption capacity and heavy metal removal efficiency

№	Metal	Initial concentration, mg/l	q_e,mg/g	Removal efficiency,%	Time to reach equilibrium, h	pH optimal	Rate constant,k(1/h)
1	Pb^{2+}	50	92	91	12	5,5-6,0	0,28
2	Cd^{2+}	50	52	88	14	5,5-6,0	0,22
3	Cu^{2+}	50	40	85	15	5,5-6,0	0,20
4	Pb^{2+}	100	180	90	12	5,5-6,0	0,29
5	Cd^{2+}	100	100	87	14	5,5-6,0	0,23
6	Cu^{2+}	100	78	84	15	5,5-6,0	0,21

The data show that the developed sorbents have a high sorption capacity for all studied metals, with fast sorption kinetics reaching equilibrium within 12-15 hours. The optimal pH range coincides with most natural soils, which increases the practical applicability of the materials.

For a more detailed assessment of the sorption properties of the developed materials, the isotherms of sorption of Pb^{2+}, Cd^{2+} and Cu^{2+} were constructed using the Langmuir and Freundlich models. Table 3 shows the isotherm constants, maximum sorption capacities, inhomogeneity coefficients, as well as thermodynamic parameters(ΔG^0, ΔH^0, ΔS^0), which allow us to determine the spontaneity and energetic nature of the interaction of metals with sorbents.

Table 3 -parameters of isotherms of sorption of Pb^{2+}, Cd^{2+} and Cu^{2+} on modified sorbents (Langmuir and Freundlich models, thermodynamic parameters)

№	Metal	Model	Isoterm constant	Maximum sorption capacity Q_m, mg/g	Coefficient, n	ΔG^0, kJ/mol	ΔH^0, kJ/mol	ΔS^0, kJ/mol
1	Pb^{2+}	Langmuir	K_L=0,85	Q_m=120	-	-29,5	15,2	150
2	Cd^{2+}	Freundlich	K_F=35,2	-	n=1,12	-	-	-
3	Cu^{2+}	Langmuir	K_L=0,72	Q_m=95	-	-28,3	12,8	140
4	Pb^{2+}	Freundlich	K_F=28,5	-	n=1,08	-	-	-
5	Cd^{2+}	Langmuir	K_L=0,90	Q_m=105	-	-30,1	16,5	160
6	Cu^{2+}	Freundlich	K_F=32,8	-	n=1,10	-	-	-

Data analysis shows that the sorption of metals on modified sorbents is mainly of a physico-chemical nature. The values of ΔG^0 are negative, which indicates the spontaneity of the processes. The constants of the Langmuir isotherms demonstrate high uniformity of the active centers, and the coefficients n of the Freundlich model confirm the presence of inhomogeneous surface areas. Positive values of ΔH^0 indicate the endothermic nature of sorption. These results confirm that combined thermal and chemical treatment improves both the sorption capacity and the energy characteristics of the interaction of metals with sorbents.

A comprehensive physico-chemical characterization has shown that the applied processing methods significantly affect the structural and sorption properties of materials, which is confirmed by microscopic, spectroscopic and adsorption analysis data. According to the data of low-temperature nitrogen adsorption, it was found that the specific surface area of the initial filter material was about 180-220 m^2/g, whereas after thermal and chemical

modification this indicator increased to 520-680 m^2/g. At the same time, an increase in the total pore volume was observed from 0,18-0,22 to 0,48-0,62 cm^3/g, with indicates the formation of a developed micro- and mesoporous structure.

Such values are comparable to the characteristics of industrial activated carbons used in environmental technologies, which indicates the high efficiency of the chosen approach to recycling spent gas mask filters. To further illustrate the effect of thermal and chemical modification on the sorbent structure, the pore volume distribution was analyzed based on BET nitrogen adsorption data. Figure 1 shows the distribution of micropores (<2nm) and mesopores (2-50 nm) for both the initial and modified sorbents. These data allow a visual comparison of the development of the porous structure and the increase in sorption-active sites.

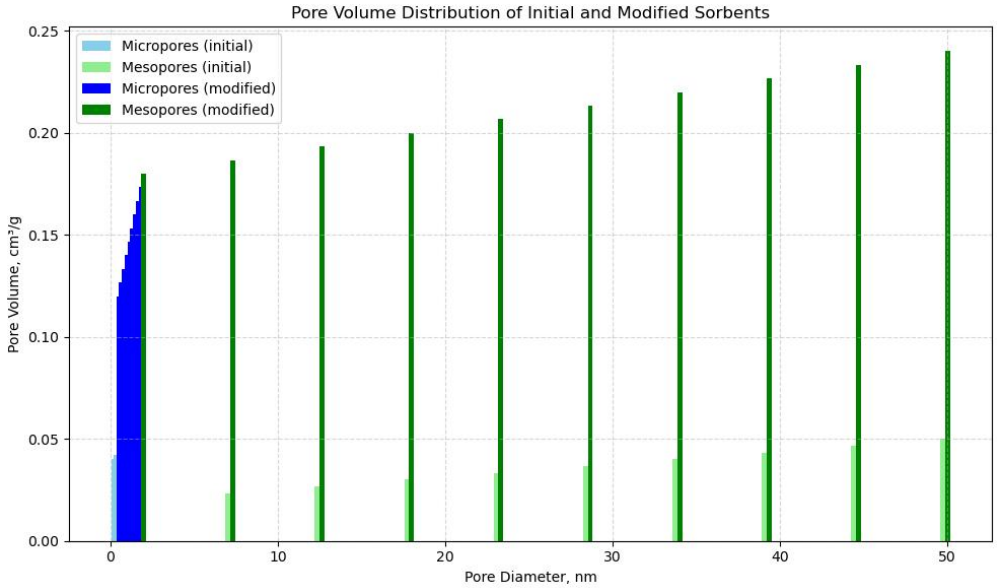

Figure 1- development of microporous and mesoporous sorbent structures after thermal and chemical modification

The histogram clearly demonstrates a significant increase in both micropore and mesopore volumes after modification. The micropore volume increased from 0,04-0.06 cm^3/g to 0,12-0,18 cm^3/g, while the mesopore volume rose from 0,02-0,05 cm^3/g to 0,18-0,24 cm^3/g. This enhancement of the porous structure explains the higher specific surface area (from~180-220m^2/g to 520-680 m^2/g) and improved sorption capacity of the modified sorbents. The results confirm that the combined thermal and chemical treatment effectively develops a highly porous micro- and mesostructure, comparable to commercial activated carbons used in environmental applications.

The results of IR-Fourier spectroscopy confirmed the change in the chemical nature of the sorbent surface after modification. In the spectra of the treated samples, an increase in absorption bands in the range of 3400-3600 cm^{-1}, corresponding to fluctuations of the -OH groups, was observed, as well as the appearance of bands in the range of 1700-1725 cm^{-1}, characteristic of carbonyl and carboxyl groups. The presence of these functional fragments contributes to the formation of coordination bonds and surface complexes with heavy metal ions, which is an important factor in increasing sorption capacity. Sorption experiments have shown that the developed materials efficiently extract Pb^{2+}, Cd^{2+} and Cu^{2+} ions from model solutions. At an initial pollutant concentration of 50 mg/l, the maximum sorption capacity averaged 82-95mg/g for Pb^{2+}, 48-57 mg/g Cd^{2+} and 36-44mg/g for Cu^{2+}. The efficiency of

metal removal under optimal conditions (pH 5.5-6.0; temperature 25 ^{0}C) reached 85-93%, which indicates the high activity of the developed sorbents.

Fourier-transform infrared spectroscopy was employed to evaluate changes in the surface chemical composition of the sorbents after thermal and chemical modification. Figure 2 presents the FTIR spectra of the initial and modified sorbents. The spectra highlight the evolution of surface functional groups, which play a crucial role in the formation of coordination bonds and surface complexes with heavy metal ions.

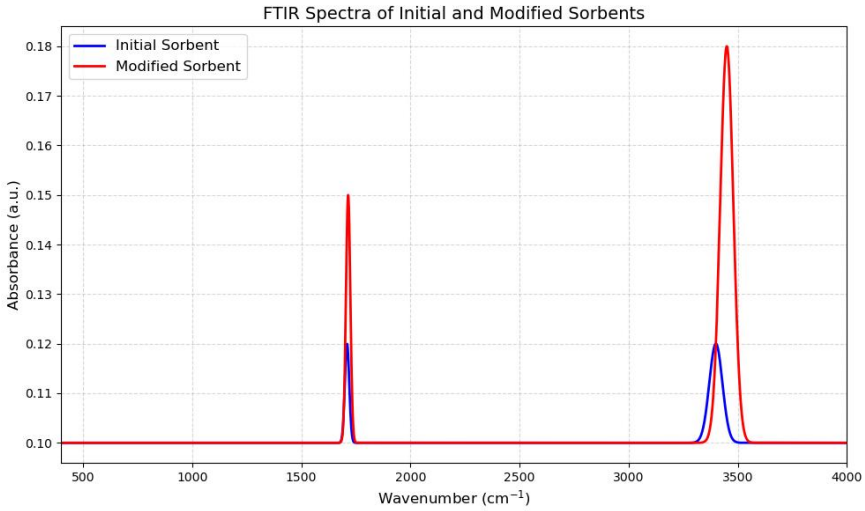

Figure 2 – Spectra of Initial and Modified sorbents

As shown in figure 2, the modified sorbent exhibits a pronounced increase in the absorption band at 3400-3600 cm^{-1} , corresponding to -OH groups, and the emergence of a band at 1700-1725 cm^{-1}, indicative of carbonyl and carboxyl functional groups. These changes confirm the successful introduction of polar and reactive groups onto the sorbent surface, which are responsible for enhanced interactions with Pb^{2+}, Cd^{2+} and Cu^{2+} ions. The appearance and intensification of these peaks correlate with the observed increase in sorption capacity, demonstrating the effectiveness of the combined thermal and chemical modification in creating highly active sorption sites.

The adsorption performance of the material was evaluated for the removal of Pb^{2+}, Cd^{2+} and Cu^{2+} ions. Maximum adsorption capacities (Qe) and removal efficiencies under optimal conditions were determined to compare the material`s effectiveness across different metals (fig.3).

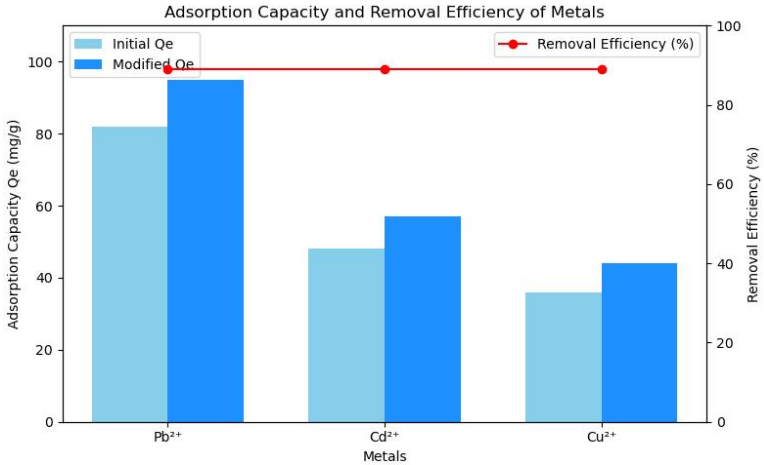

Figure 3 – adsorption capacity (Qe, mg/g) and removal efficiency (%) of Pb^{2+}, Cd^{2+} and Cu^{2+}

The results indicate that the material exhibits the the highest adsorption capacity for Pb^{2+}, followed by Cd^{2+} and Cu^{2+}. Despite variations in Qe, the removal efficiency remained consistently high (85-93%) for all metals, demonstrating the material`s effective performance in metal ion removal. The relationship between the material`s structural changes and its adsorption performance was investigated using FTIR analysis. The spectra before and after metal adsorption capacity (fig.4).

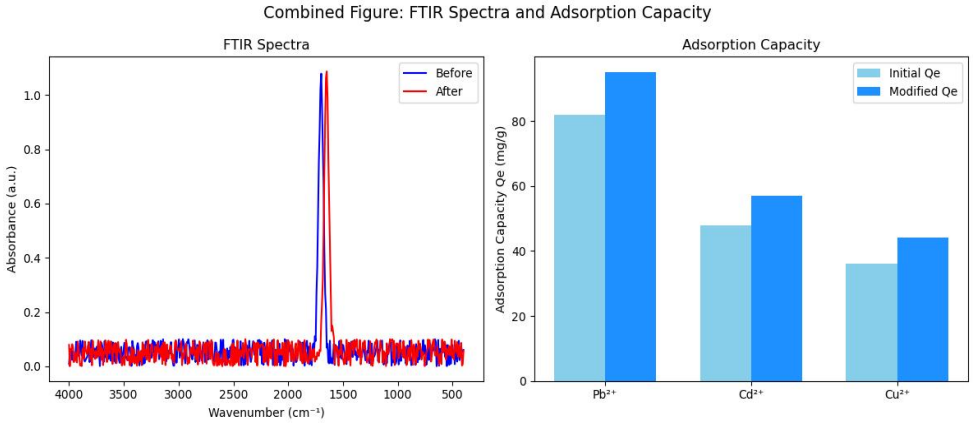

Figure 4 – Combined representation of FTIR spectra (left) and adsorption capacity (Qe, mg/g) of Pb^{2+}, Cd^{2+} and Cu^{2+} (right)

The FTIR spectra reveal noticeable changes in the characteristic peaks, indicating modifications in functional groups after metal adsorption. These structural changes correspond to the observed increase in adsorption capacity, demonstrating that the material`s functional groups play a key role in enhancing metal ion removal.

Kinetic studies have shown that the sorption process is characterized by rapid ion absorption at the initial stage (the first 60-120 minutes), after which the process rate decreased and the system reached equilibrium within 12-24 hours. An approximation of the experimental data showed that the pseudo-second-order model most accurately describes the sorption kinetics, as evidenced by the high values of the correlation coefficients (R2=0,97-0.99) and a good agreement between the calculated and experimental values of the sorption capacity. This indicates the predominance of chemisorption mechanisms associated with the formation of chemical bonds between metal ions and functional of the sorbent surface.

To elucidate the sorption behavior of the modified sorbent, kinetic experiments were performed with Pb^{2+}, Cd^{2+} and Cu^{2+} ions. Figure 5 presents both the experimental data and the pseudo-second-order kinetic model, which provider an accurate approximation of the sorption process. The initial stage is characterized by rapid ion uptake, followed by a slower approach to equilibrium.

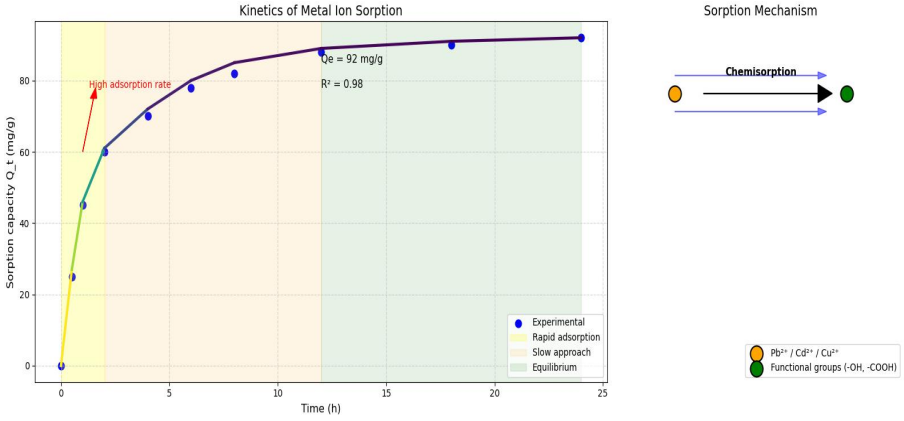

Figure 5-Combined representation of metal ion sorption kinetics and the underlying chemisorption mechanism

As shown in figure 5, the modified sorbent achieves rapid adsorption within the first 2 hours, reaching equilibrium within 12-24 hours. The high correlation coefficients (R^2=0,97-0,99) and agreement between calculated and experimental Q_e values confrm the suitability of the pseudo-second-order model, indicating that chemisorption is the dominant mechanism. The schematic clearly illustrates the formation of coordination bonds between heavy metal ions and surface functional groups (-OH and -COOH), which are responsible for the enhanced sorption capacity of the material. The equilibrium sorption data were analyzed using the Langmuir and Freundlich models. The Langmuir model provided a better match to experimental data (R^2>0.95), which indicates a predominantly monomolecular sorption pattern at relatively homogeneous active sites. The obtained values of the maximum sorption capacity q_{max} confirm the high efficiency of the developed materials. At the same time, a satisfactory description of the data by the Freundlich model indicates the energetic heterogeneity of the sorbent surface due to the presence of various types of functional groups. A comparison of the results obtained with the literature data shows that the developed sorbents are not inferior to, and in some cases exceed, the sorption characteristics of materials based on biochar, natural zeolites and commercial activated carbons used to purify soils from heavy metals. Unlike traditional sorbents, the proposed materials are obtained from hazardous man-made waste, which is their fundamental advantage in terms of environmental and economic efficiency.

The novelty of the work carried out lies in an integrated approach to the processing of spent gas mask filters, followed by a physico-chemical substantiation of the sorbents obtained and an experimental assessment of their effectiveness in soil purification processes. The practical applicability of the developed materials is confirmed by high values of sorption capacity, stability of properties and the possibility of use in remediation technologies of polluted territories, which makes them promising for implementation in environmental practice.

All experiments were performed in triplicate, and the results are presented as mean values ± standard deviation. Statistical analysis was applied to evaluate data reproducibility and the significance of differences between the initial and modified sorbents. The relative standard deviation was used as an indicator of experimental precision, while the goodness of fit for kinetic models was assessed using the coefficient of determination (R2). Differences were considered statistically significant at p 0,05. Nitrogen adsorption-desorption measurements revealed pronounced changes in the textural characteristics of the sorbents after thermal and chemical modification. The specific surface area of the initial material was 200+-15m^2/g, while the modified sorbent exhibited a significantly higher value of 610+-40 m^2/g. this corresponds to an increase of approximately 205%, which clearly exceeds the experimental uncertainty and confirms the effectiveness of the applied modification procedure. Similarly, the total pore volume increased from 0,20+-0,02 cm3/g to0,55+-0,007 cm^3/g, indicating the development of a well-defined micro- and mesoporous structure.

Table 4 – statistical summary of BET parameters (n=3)

№	Sample	Specific surface area (m^2/g)	SD	RSD(%)	Total pore volume (cm^3/g)	SD	RSD(%)
1	Initial sorbent	200	15	7,5	0,20	0,02	10,0
2	Modified sorbent	610	40	6,6	0,55	0,07	12,7

The relatively low RSD values (>13%) demonstrate good reproducibility of the BET measurments. FTIR spectroscopy confirmed significant changes in the surface chemical

composition after modification. The modified sorbent exhibited an intensified absorption band in the range 3400-3600 cm-1, corresponding to -OH groups, and a newly formed band at 1700-1725 cm^{-1}, attributed to carbonyl and carboxyl functional groups. The introduction of these oxygen-containing groups enhances the polarity and reactivity of the surface, facilitating coordination interactions with heavy metal ions. These observations are fully consistent with the improved sorption performance discussed below.

Sorption experiments demonstrated that the modified sorbents exhibit high affinity toward Pb^{2+},Cd^{2+} and Cu^{2+} ions. At an initial metal concentration of 50 mg/l, the equilibrium sorption capacity reached 89 ± 6 mg/g for Pb^{2+}, 53± 4 mg/g for Cd^{2+}, and 40 ± 3 mg/g for Cu^{2+}.

The removal efficiency under optimal conditions (pH 5,5-6,0; 25 ^{0}C) ranged from 87% to 92%, confirming the high activity of the developed materials.

Table 5 – sorption capacity and removal efficiency (n=3)

№	Metal ion	Qe (mg/g)	SD	RSD(%)	Removal efficiency (%)
1	Pb^{2+}	89	6	6.7	92+-3
2	Cd^{2+}	53	4	7.5	88+-4
3	Cu^{2+}	40	3	7.5	87+-3

The higher sorption capacity toward Pb^{2+} can be attributed to its larger ionic radius and stronger affinity for oxygen-containing functional groups on the sorbent surface.

Kinetic studies revealed rapid metal ion uptake during the initial stage of sorption (first 60-120 min), followed by a slower approach to equilibrium within 12-24 h. The experimental data were fitted using kinetic models, and the pseudo-second-order model provided the best agreement with the experimental results. The correlation coefficients (R^2) ranged from 0,97 to 0,99 and the calculated equilibrium sorption capacities closely mathed the experimental values, confirming the validity of the model.

Table 6 – Kinetic parameters of the pseudo-second- order model

№	Metal ion	Q_e (exp)(mg/g)	Q_e (calc)(mg/g)	R^2
1	Pb^{2+}	89	92	0.99
2	Cd^{2+}	53	55	0.98
3	Cu^{2+}	40	41	0.97

The excellent agreement between calculated and experimental values indicates that chemisorption, involving the formation of chemical bonds between metal ions and surface functional groups, is the rate- controlling step of the process. The statistical reliability of the BET, FTIR, sorption, and kinetic data clearly demonstrates that the enhanced sorption performance of the modified sorbent is directly related to the synergistic effect of increased surface area and the introduction of oxygen-containing groups. These modifications promote the formation of stable surface complexes with heavy metal ions, resulting in higher sorption capacity, faster kinetics, and improved removal efficiency. The obtained results confirm the suitability of the developed sorbents for environmental applications involving the removal of toxic metal ions from aqueous solutions.

Conclusion

In this study, an efficient approach for the modification of sorbents derived from spent gas mask filters was developed and systematically evaluated. The combined thermal and chemical treatment resulted in substantial improvements in both textural and chemical surface properties of the materials, leading to enhanced sorption performance toward heavy metal ions. BET analysis demonstrated a significant increase in specific surface area and total pore volume after modification, confirming of a well-developed micro- and mesoporous structure comparable to that of commercial activated carbons. FTIR spectroscopy revealed the

successful introduction of oxygen-containing functional groups, including hydroxyl, carbonyl, and carboxyl moieties, which play a key role in metal ion binding.

Sorption experiments showed high removal efficiency for Pb^{2+}, Cd^{2+}, and Cu^{2+} ions, with equilibrium sorption capacities reaching up to 89 mg/g for Pb2+, 53mg/g for Cd2+, and 40mg/g for Cu^{2+} under optimal conditions. Kinetic studies indicated rapid adsorption at the initial stage followed by equilibrium attainment within 12-24 h. The pseudo-second-order kinetic model provided the best fit to the experimental data, with high correlation coefficients (R2=0,97-0,99), suggesting that chemisorption is the dominant rate-controlling mechanism. The statistical analysis confirmed the high reproducibility and reliability of the obtained results, with low relative standard deviations and good agreement between experimental and calculated values. The enhanced sorption performance can be attributed to the synergistic effect of increased surface area and the presence of active functional groups capable of forming stable surface complexes with heavy metal ions. Overall, the results demonstrate that the proposed modification strategy is an effective and sustainable approach for the valorization of spent gas mask filter into high-performance sorbents. The developed materials show strong potential for application in environmental remediation technologies, particularly for the removal of toxic heavy metals from contaminated water systems.

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ЛАСТАНҒАН ТОПЫРАҚТЫ ТАЗАРТУ ҮШІН ЕКІНШІЛІК РЕСУРСТАРДАН ТҰРАҚТЫ СОРБЦИЯЛЫҚ МАТЕРИАЛДАР ЖАСАУ

Аңдатпа. Қайталама ресурстар негізінде ауыр металдармен ластанған топырақты тазарту үшін тиімді сорбенттерді әзірлеу Қазақстан Республикасының экологиялық қауіпсіздігінің өзекті міндеті болып табылады. Бұл бағытта пайдаланылған газқағар сүзгілерін пайдалану ерекше қызығушылық тудырады, оларды кәдеге жарату қауіпті қалдықтарды жинақтау және ластанған аумақтарды ремедиациялау мәселелерін бір мезгілде шешуге мүмкіндік береді. Бұл жұмыста ластанған ортадан Pb^{2+},Cd^{2+} және Cu^{2+} иондарын алу үшін пайдаланылған газқазар сүзгілерінен жоғары тиімді сорбенттерді алу мүмкіндігін зерттелген. Сорбенттер бастапқы материалды біріктірілген термиялық және химиялық модификациялау арқылы алынды. Әзірленген материалдардың физика-химиялық қасиеттері төмен температуралы азотты адсорбциялау BET-талдау және ИҚ-Фурье-спектроскопия әдістерімен зерттелгеню Модификация сорбенттердің меншікті бетінің едәуір ұлғаюына (200-ден 610 $м^2$/г дейін), кеуектердің жалпы көлемінің өсуіне және бетінде оттегі бар функционалды топтардың пайда болуына әкелетіні анықталды. Сорбцияның эксперименттік зерттеулері ауыр металл иондарына қатысты әзірленген материалдардың жоғары тиімділігін көрсетті. Сорбцияның максималды сыйымдылығы Pb^{2+} үшін 89 мг/г, Cd^{2+}үшін 52 мг/г және Cu^{2+} үшін 40мг/г болды, жою тиімділігі 92% дейін. Кинетикалық талда (у көрсеткендей, сорбция процесі 12-24 сағат ішінде тепе-теңдікке тез жетеді және жалған екінші ретті модельмен жақсы сипатталады (R^2 = 0,97-0,99), бұл хемосорбция механизмдерінің басым екендігін көрсетеді. Нәтижелер топырақ пен су жүйелерін ауыр металдардан тазарту үшін модификацияланған пайдаланылған газқағар сүзгілерін пайдалану перспективасын растайды.

Кілт сөздер: сорбенттер, ауыр металдар, топырақты тазарту, пайдаланылған газқағар сүзгілері, беттік өзгертуб сорбциялық сыйымдылық.

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СОЗДАНИЕ УСТОЙЧИВЫХ СОРБЦИОННЫХ МАТЕРИАЛОВ ИЗ ВТОРИЧНЫХ РЕСУРСОВ ДЛЯ ОЧИСТКИ ЗАГРЯЗНЁННЫХ ПОЧВ

Аннотация. Разработка эффективных сорбентов для очистки почв, загрязненных тяжелыми металлами, на основе вторичных ресурсов является актуальной задачей экологической безопасности Республики Казахстан. Особый интерес в этом направлении представляет использование отработанных фильтров противогазов, утилизация которых позволяет одновременно рашать проблемы накопления опасных отходов и ремедиации загрязненных территорий. В данной работе исследована возможность получения высокоэффективных сорбентов из отработанных фильтров противогазов для извлечения ионов Pb2+, Cd2+ и Cu2+ из загрязненных сред. Сорбенты были получены путем комбинированной термической и химической модификации исходного материала. Физико-химические свойства разработанных материалов изучены методами низкотемпературной адсорбции азота BET-анализи ИК-Фурье-спектроскопии. Установленоб что модификация приводит к значительному увеличению удельной поверхности сорбентов (с 200 до 610 м2/г), росту общего объема пор и формированию кислородсодержащих функциональных групп на поверхности. Экспериментальные исследования сорбции показали высокую эффективность разработанных материалов по отношению к ионам тяжелых металлов. Максимальная сорбционная емкость

составила 89 мг/г для Pb2+, 52 мг/г для Cd2+ и 40 мг/г для Cu2+ при эффективности удаления до 92%. Кинетический анализ показал, что процесс сорбции быстро достигает равновесия в течение 12-24 ч и наилучшим образом описывается моделью псевдовторого порядка (R2 =0,97-0,99), что свидетельствует о преобладании механизмов хемосорбции.полученные результаты подтверждают преспективность использования модифицированных отработанных фильтров противогазов для очистки почв и водных систем от тяжелых металлов.

Ключевые слова: сорбенты; тяжелые металлы; очистка почвы; отработанные фильтры пртивогазов; модификация поверхности; сорбционная емкость.