Original article
УДК 544.723.21
DOI: 10.37482/0536-1036-2025-3-184-194

Purification of Liquid Radioactive Waste with Activated Carbon from Sludge-Lignin

Ekaterina S. Loginova (Kokina)[1]✉***, Senior Lecturer;*** *ResearcherID: [HMP-6017-2023](HMP-6017-2023),*
ORCID: https://orcid.org/0000-0001-8576-3338
Tatyana E. Boykova[1]***, Candidate of Engineering, Assoc. Prof.;***
ResearcherID: AAK-1789-2020, ORCID: https://orcid.org/0000-0002-4589-4015
Nikolay I. Bogdanovich[2]***, Doctor of Engineering, Prof.;*** *ResearcherID: A-4662-2013,*
ORCID: https://orcid.org/0000-0002-5374-2943
Konstantin B. Vorontsov[2]***, Candidate of Engineering, Assoc. Prof.;***
ResearcherID: P-2313-2019, ORCID: https://orcid.org/0000-0001-6369-7245
[1]Northern (Arctic) Federal University named after M.V. Lomonosov, ul. K. Voronina, 6, Severodvinsk, 164500, Russian Federation; e.kokina@narfu.ru✉, t.boykova@narfu.ru
[2]Northern (Arctic) Federal University named after M.V. Lomonosov, Naberezhnaya Severnoy Dviny, 17, Arkhangelsk, 163002, Russian Federation; k.vorontsov@narfu.ru

Received on January 22, 2025 / Approved after reviewing on March 16, 2025 / Accepted on March 18, 2025

Abstract. In this article, the authors have carried out a study of the synthesis of carbon sorbents from sludge-lignin by thermochemical activation and determination of their adsorption properties. Sludge-lignin is a large-tonnage waste generated during coagulation treatment of wastewater from pulp and paper mills. The promising development of technological solutions for waste disposal is complicated by the complex chemical composition of the sludge and the lack of practical demand for potential products that can be obtained as a result of its processing. One of the possible areas of use of by-products of processing is the synthesis of activated sorbents for wastewater treatment from heavy metals and radionuclides. To study the effect of independent parameters on the adsorption properties of activated carbons, an experiment has been conducted using a second-order rotatable central composite design. Based on experimental data, regression equations for the adsorption activity of iodine and methylene blue have been derived. The porous structure of the coal surface has been analysed using the ASAP 2020 MR automated system. The pore volumes of the activated sorbents from sludge-lingin have been determined using the Brunauer-Emmett-Teller and Barrett-Joyner-Halenda methods. During the experiment, optimal pyrolisis conditions have been identified: pyrolysis temperature 700 °C, pyrolysis duration 60 min and the activating agent dosage 180 %. This mode is economically advantageous for the formation of high-performance carbon sorbents due to the low consumption of alkali compared to other types of lignin. The authors have studied sorbents obtained under optimal conditions. The sorption properties have been analyzed by the spectrometric method with respect to various radionuclides (cesium, cobalt, strontium, etc.). Energy spectra have been constructed using the SpectraLine GP (Gamma Precision) software package, and the initial and final activity of radionuclides has been calculated. It has been determined that carbon sorbents obtained from sludge-lingin by thermochemical activation can be used for the selective extraction of certain radionuclides with an efficiency of up to 94 %.

Keywords: adsorption properties, activated carbons, synthesis, sludge-lignin, radionuclides

For citation: Loginova (Kokina) E.S., Boykova T.E., Bogdanovich N.I., Vorontsov K.B. Purification of Liquid Radioactive Waste with Activated Carbon from Sludge-Lignin. *Lesnoy Zhurnal* = Russian Forestry Journal, 2025, no. 3, pp. 184–194. (In Russ.).
https://doi.org/10.37482/0536-1036-2025-3-184-194

Научная статья

Очистка жидких радиоактивных отходов активированным углем, полученным из шлам-лигнина

Е.С. Логинова (Кокина)[1✉]***,*** *ст. преподаватель; ResearcherID: HMP-6017-2023, ORCID: https://orcid.org/0000-0001-8576-3338*
Т.Е. Бойкова[1]***,*** *канд. техн. наук, доц.; ResearcherID: AAK-1789-2020, ORCID: https://orcid.org/0000-0002-4589-4015*
Н.И. Богданович[2]***,*** *д-р техн. наук, проф.; ResearcherID: A-4662-2013, ORCID: https://orcid.org/0000-0002-5374-2943*
К.Б. Воронцов[2]***,*** *канд. техн. наук, доц.; ResearcherID: P-2313-2019, ORCID: https://orcid.org/0000-0001-6369-7245*
[1]Северный (Арктический) федеральный университет им. М.В. Ломоносова, ул. К. Воронина, д. 6, г. Северодвинск, Россия, 164500; e.kokina@narfu.ru✉, t.boykova@narfu.ru
[2]Северный (Арктический) федеральный университет им. М.В. Ломоносова, наб. Северной Двины, д. 17, г. Архангельск, Россия, 163002; k.vorontsov@narfu.ru

Поступила в редакцию 22.01.25 / Одобрена после рецензирования 16.03.25 / Принята к печати 18.03.25

Аннотация. Исследован синтез углеродных сорбентов из шлам-лигнина методом термохимической активации и определены их адсорбционные свойства. Шлам-лигнин – это крупнотоннажный отход, образующийся при коагуляционной очистке сточных вод целлюлозно-бумажных комбинатов. Проблемой при утилизации отхода является сложный химический состав осадка и отсутствие спроса на потенциальные продукты, которые могут быть получены в результате его переработки. В число возможных направлений использования побочных продуктов переработки входит синтез активированных сорбентов для очистки сточных вод от тяжелых металлов и радионуклидов. Для изучения влияния независимых параметров на адсорбционные свойства активированных углей был проведен эксперимент с применением ротатабельного центрального композиционного плана 2-го порядка. На основании экспериментальных данных выведены уравнения регрессии для адсорбционной активности иода и метиленового синего. Пористая структура поверхности углей анализировалась с помощью автоматизированной системы ASAP 2020 MR. По методикам Брунауэра–Эммета–Теллера и Баррета–Джойнера–Халенды определяли объемы пор активированных сорбентов из шлам-лигнина. В ходе эксперимента выявлены оптимальные условия режима пиролиза: температура – 700 °С, продолжительность – 60 мин и дозировка активирующего агента – 180 %. Данный режим является экономически выгодным для формирования высокоэффективных углеродных сорбентов по причине не очень высокого расхода щелочи по сравнению с другими видами лигнинов. Исследованы сорбенты, полученные при оптимальных условиях. Спектрометрическим методом проведен анализ сорбционных свойств по отношению к различным радионуклидам (цезий, кобальт, стронций и т. д). С помощью программного комплекса SpectraLine GP (Gamma Precision) построены энергетические спектры, затем рассчитаны начальная и конечная активности радионуклидов. Определено, что углеродные сорбенты, полученные из шлам-лигнина методом термохимической активации, возможно применять для селективного извлечения некоторых радионуклидов с эффективностью до 94 %.

Ключевые слова: адсорбционные свойства, активированные угли, синтез, шлам-лигнин, радионуклиды

Для цитирования: Loginova (Kokina) E.S., Boykova T.E., Bogdanovich N.I., Vorontsov K.B. Purification of Liquid Radioactive Waste with Activated Carbon from Sludge-Lignin // Изв. вузов. Лесн. журн. 2025. № 3. С. 184–194. https://doi.org/10.37482/0536-1036-2025-3-184-194

Introduction

Sludge-lignin is a large-tonnage waste generated the process of coagulation treatment of wastewater from pulp and paper mills with aluminum sulfate. The waste is a multicomponent colloidal system, mainly consisting of a large amount of aluminum hydroxides (11–13 %) and organic substances such as lignin, resin acids, organosulphur and other hazardous substances [8, 9, 18].

For 40 years of continuous operation, the coagulation treatment method has been used at the Baikalsk Pulp and Paper Mill [14]. By the time the plant was put into operation (1966), there was no technology for processing sludge-lingin. Therefore, it was stored in liquid form in sedimentation tanks. Design solutions for the disposal of sludge-lingin have not yet been developed, therefore, during the period of operation, 7 sludge-lingin storage sites have been created, containing more than 8 mln m^3 of waste [9].

The prospects for developing technological solutions for the disposal of sludge-lingin are hampered by its complex chemical composition and the lack of practical demand for possible products obtained after its processing. Theoretically, the use of sludge-lingin is possible as a raw material for obtaining composts and fertilizers [7, 19], and for the preparation of drilling fluids by geological enterprises [12]. The ash from the combustion of sludge-lingin can be used for the production of building materials [10–12]. It is also possible to produce sorbents and coagulants for the physical and chemical treatment of wastewater [6].

Currently, there are many methods for obtaining carbon sorbents from technical lingins, one of which is pyrolisis with thermochemical activation [20]. NaOH is considered to be an effective chemical reagent for activating carbon materials with a disordered structure [17]. In Russia, similar studies were first conducted in the early 2000s [3] and continue to this day at the Northern (Atctic) Federal University.

The aim of this study has been to synthesize carbon adsorbents from sludge-lignin by thermochemical activation and to study their adsorption properties with respect to radioactive isotopes.

Research Objects and Methods

The coagulation process has been carried out in the laboratory of the Department of Pulp and Paper Technology of the Northern (Arctic) Federal University named after M.V. Lomonosov from model solutions with aluminum sulfate, in accordance with the optimal conditions determined during preliminary studies [16]. A model lignin-containing solution has been used with the following parameters:

lignin concentration – 400 mg/l, chromaticity – 1800 PCU according to the method [16]. The resulted sludge-lignin has been subjected to mechanical dehydration on filter presses, dried and pyrolysed with thermochemical activation with NaOH. In order to reduce the number of necessary experiments and study the influence of factors in their possible combinations, the experiment has been carried out using the method of the second-order rotatable central composite design (RCCD) for 3 factors: pyrolysis temperature (T_{pyr}, °C), the activating agent dosage (D_{NaOH}, %) and pyrolysis duration (τ, min) (Table 1).

Table 1

The levels of variation of input parameters

Levels of variation of independent variables	Input parameters		
	Pyrolysis temperature (X_1), °C	Pyrolysis duration (X_2), min	Activating agent dosage (X_3), %
–α	650	30	120
–1	670	42	144
0	700	60	180
+1	730	78	216
+α	750	90	240

Based on the experimental data obtained, using regression analysis methods, the coefficients of the regression equations have been calculated. In general, the regression equation looks as follows:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + b_{33}x_3^2 + b_{12}x_1x_2 + \\ + b_{13}x_1x_3 + b_{23}x_2x_3,$$

where x_i is represented in coded variables

The independent variables have varied on 5 levels. The following levels of variation of independent variables have been distinguished: $\pm\propto; \pm 1; 0$.

During the laboratory test, the adsorption properties for iodine have been assessed in accordance with GOST 33618–2015 and for methylene blue [4] according to the method described in [16].

The automated system ASAP 2020 MR has been used to determine the porous structure of the coal surface. The experiment has been carried out at a temperature of –196 °C. Using the appropriate software, nitrogen adsorption-desorption isotherms from the gas phase have been obtained as a result.

The determination of the adsorption capacity of the obtained activated carbons in relation to radioactive isotopes has been carried out in the laboratory of the Department of Physics and Environmental Engineering Protection of the Institute of Shipbuilding and Arctic Marine Engineering at a liquid medium temperature of t = 23±2 °C in accordance with GOST 33587–2015. The construction of radionuclide energy spectra, automatic determination of radionuclide composition, calculation of peak parameters, calculation of radionuclide activity and measurement errors have been carried out automatically using the SpectraLineGP software package. Previous studies have confirmed [5] that the pH of the medium affects the recovery ratio of heavy metals and radionuclides from aqueous solutions [2]. Therefore, an alkaline medium (pH = 10) has been chosen as the optimal medium for the extraction of cobalt ions. The required medium has been created by alkalizing the solution with ammonia water. In this case, a complex cobalt compound has been obtained [5].

Results and Discussion

During the experiment, data have been obtained that have been used to develop statistical models describing the relationship between the values of the input parameters and the pyrolysis conditions. The adequacy of the model has been checked using the F-criterion (Fisher's criterion). The calculated criterion has not exceeded the critical one, which confirms the adequacy of the obtained models (at the significance level $\alpha = 0.05$).

When modeling the adsorption properties of iodine with carbon sorbents from sludge-lingin, the regression equation has been obtained:

$$Ai_2 = 179.61 + 37.37X_3 - 10.63X_1X_2 + 26.88X_1X_3 - 7.13X_1^2 + \\ + 23.82X_2^2 - 7.13X_3^2.$$

When analyzing the equation, it can be seen that the negative coefficients at X_1^2 and X_3^2 indicate the extremum of the response surface relative to the pyrolysis temperature and the activating agent dosage. In addition, the positive value of the coefficient indicates the nature of the surface in relation to the duration of the pyrolysis process. The response surfaces have been plotted for the regression equation obtained (Fig. 1).

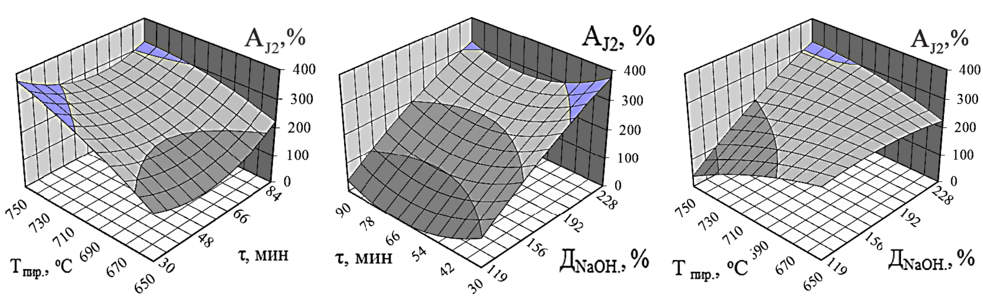

Fig. 1. The influence of regime parameters on iodine sorption capacity

Analysing the surfaces obtained (Fig. 1), it should be noted that a simultaneous increase in the pyrolysis temperature and alkali dosage has a positive effect on the development of iodine sorption capacity. Due to the economic feasibility, the optimal combination is a pyrolysis temperature of 700 °C and the activating agent dosage of 180 %.

When modelling the dependence of the specific adsorption of methylene blue on various parameters, the following regression equation has been obtained:

$$A_{\text{MB}} = 680.79 - 40.67X_1 + 130.74X_2 + 60.00X_1X_3 + 57.00X_2X_3 + \\ + 53.28X_2^2 - 33.01X_3^2.$$

For clarity, the response surfaces have been, which are presented in Fig. 2.

It is obvious that the specific adsorption is positively influenced by the dosage of NaOH and the combined effect (increase) of 2 factors: pyrolisis temperature and alkali dosage (Fig. 2). It should be noted that increasing only the pyrolisis temperature without changing other factors leads to a significant reduction in the specific adsorption of methylene blue. Thus, the optimal combination is a pyrolysis temperature of 700 °C and the activating agent dosage of 180 %, which is equally effective for the formation of adsorption properties for iodine and methylene blue.

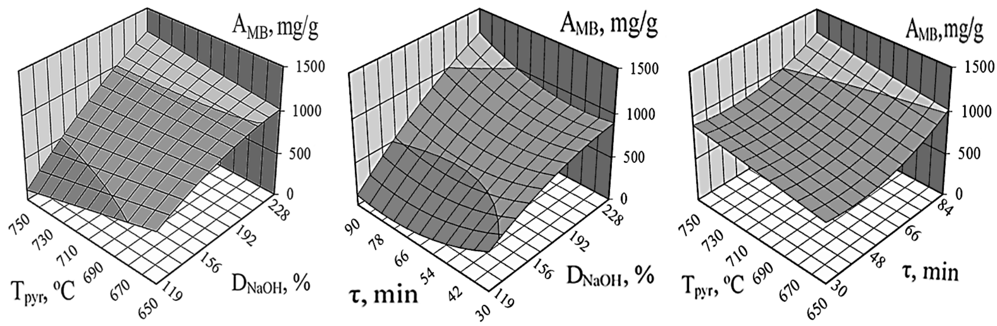

Fig. 2. The influence of independent parameters on the specific adsorption of methylene blue by carbon sorbents from sludge-linging

The Brunauer–Emmett–Teller (BET) method has been used to describe polymolecular adsorption and the relationship between the adsorption of a substance and its saturated vapor pressure. The resulting mathematical model illustrating the influence of experimental factors is represented by the following regression equation:

$$V_{\mathrm{BET}} = 0.36 + 0.15X_3 - 0.06X_1X_2 + 0.07X_1X_3.$$

Analyzing the equation, it is clear that the pore volume depends on the activating agent dosage and the combined effect of 2 factors: temperature – dosage and temperature – pyrolysis duration.

Based on this equation, the response surfaces have been plotted (Fig. 3).

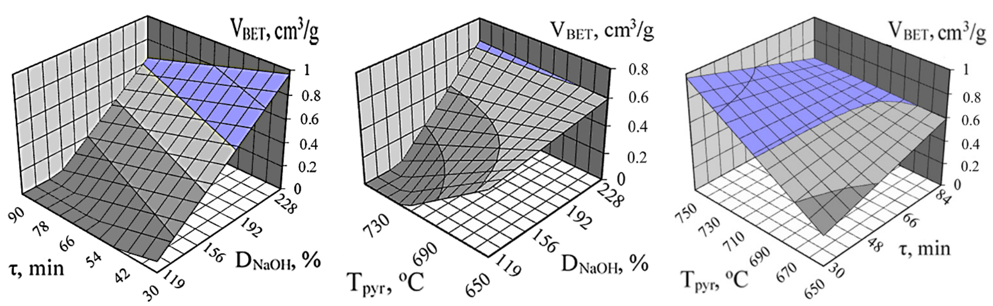

Fig. 3. The influence of experimental factors on the volume of V_{BJH} micropores with carbon sorbents from sludge-lignin

It is obvious that the volume of micropores is positively affected by an independent increase in the activating agent dosage and its increment with temperature growth. The negative influence is imposed by the combined effect of temperature and an increase in the duration of pyrolysis. Thus, the optimal mode for the formation of micropores in synthesised coals is a pyrolysis temperature of 700 °C and the activating agent dosage of 180 %.

To determine the volume of mesopores, calculations have been performed using the Barrett-Joyner-Halenda (BJH) method. As a result, a mathematical model has been obtained:

$$V_{\mathrm{BJH}} = 0.08 + 0.07X_3 + 0.03X_1X_3 + 0.05X_3^2.$$

The response surfaces corresponding to the regression equation are shown in Fig. 4.

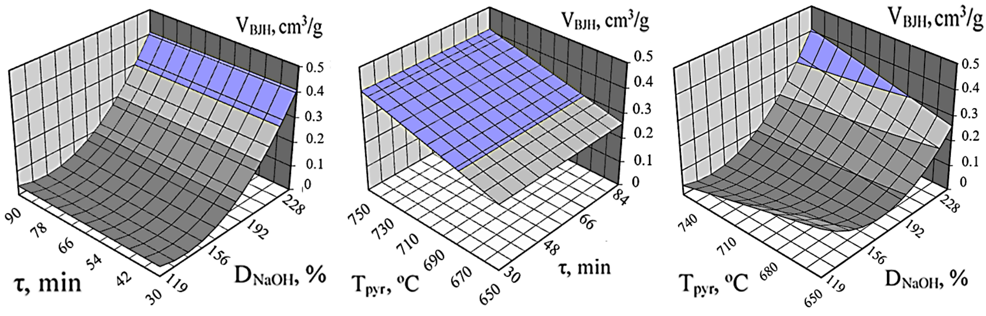

Fig. 4. The influence of experimental factors on the volume of mesopores of carbon sorbents from sludge-lignin

A beneficial effect on the volume of mesopores of carbon sorbents from sludge-lignin is achieved by increasing the dosage of the agent and the combined effect of temperature and dosage.

Thus, the optimal mode for the formation of micro- and mesopores, the adsorption capacity for iodine and methylene blue in synthesised carbons is a pyrolysis temperature of 700 °C and the activating agent dosage of 180 %.

Activated carbons synthesised in accordance with the optimal combination of factors (T = 700 °C, τ = 60 min and D_{NaOH} = 180 %) have been used to purify liquid radioactive waste from a ship repair plant. 0.01 g of activated carbon has been added to a 200 ml sample under analysis and stirred on a magnetic stirrer at a speed of 1,500 rpm for 15 min. At the end of the experiment, the sample has been filtered and the analysed solution has been taken for further sample preparation. The liquid sample has been subjected to evaporation. As a result, a counting sample has been obtained, which is a stainless steel disc on which elemental isotopes are electrolytically deposited. The prepared disc has been analysed and accompanied by a protocol stating the disc number and the sample name.

In the Methodology for Measuring the Activity of Gamma-Emitting Nuclides in Counting Samples Using a Semiconductor Spectrometer [15], a method and algorithm for measuring the specific or volumetric activity of a gamma-emitting nuclide have been established. The activity has been measured by counting pulses at the peaks of total absorption represented in the hardware spectra. A hardware spectrum is a discrete distribution: along the abscissa axis – the channel numbers (energy $E\gamma$) and along the ordinate axis – the number of pulses accumulated in the channels (imp/s). This histogram is further approximated by a smooth curve using various mathematical models, e.g. the Gaussian function. In order to correlate channel numbers with gamma-quanta energy values, the spectrometer is pre-calibrated using the energy of standard sources.

The smoothed radionuclide spectra obtained in the original sample (Fig. 5) and after sorption (Fig. 6) have been processed using an inbuilt tool for peak detection and calculation of radionuclide activity. One of the crucial aspects when calculating activity is the degree of identification of peaks in the spectrum. It can be unambiguous, i.e. each peak corresponds to no more than 1 library line, and ambiguous, when several library lines may correspond to a peak. For this purpose, a procedure for identifying pre-detected peaks is carried out according to the equation:

$$S = A_1Y_{1i} + A_2Y_{2i} + \ldots + A_nY_{ni},$$

where S is the area of the peak; A_n is the n-radionuclide activity; Y_n is the n-radionuclide line intensity.

The spectra processing algorithm is presented in Fig. 5 and 6. The calculation results are presented in Table 2.

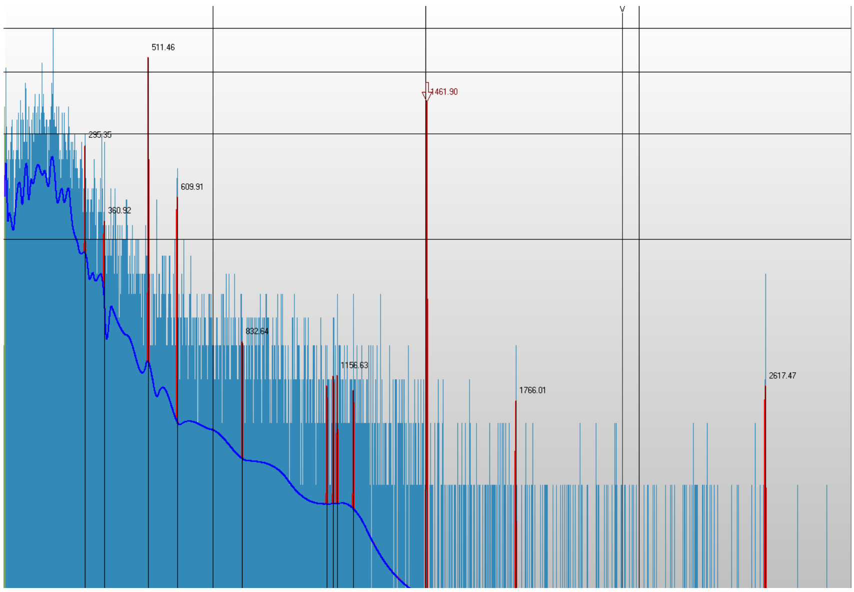

Fig. 5. The energy spectra of the sample before sorption

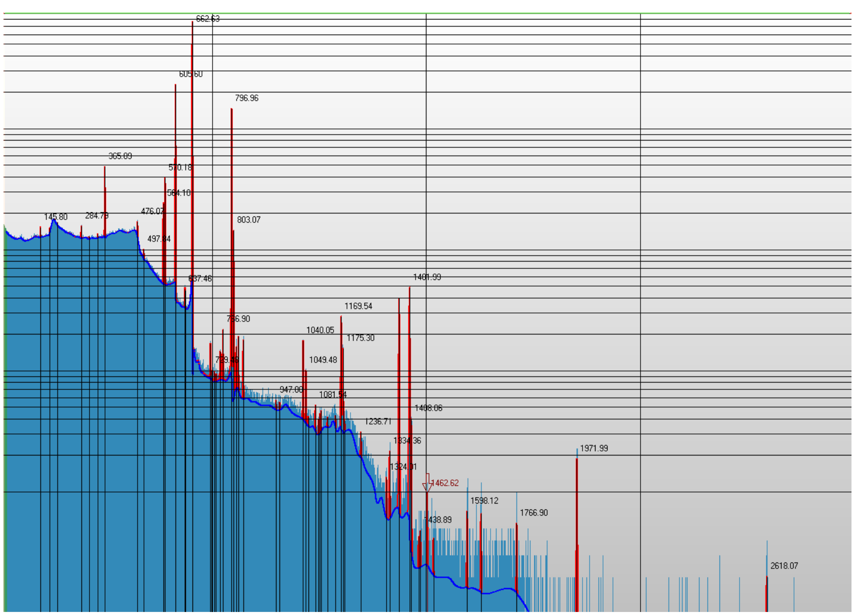

Fig. 6. The energy spectra of the sample after sorption

Based on the results of the calculated initial and final specific activity, the sorption efficiency has been calculated. It has been estimated based on the amount of sorbed radionuclides from liquid radioactive waste per 1 g of coal. The results obtained are presented in Table 2.

Table 2

The isotopic composition of the analyzed solution

Isotopic composition	Initial specific activity, Bq/kg	Final specific activity, Bq/kg	Purification efficiency, %
Nb-95	660	110	83
Mn-54	380	50	86
Cs-137	160,000	134,000	16
Cs-134	41,000	35,000	14
Sr-90	800	47	94

Based on the research results, it can be noted that sorbents are most effective for the selective extraction of strontium, niobium and manganese radionuclides (the atomic radius of radionuclides varies from 140 to 215 pm). The cesium radionuclide has an atomic radius of 267 pm, which prevents the atom from penetrating through the porous structure of activated carbon [7].

Conclusion

The study has revealed that carbon adsorbents obtained from sludge-lignin with thermochemical activation by alkali (NaOH) have high adsorption properties.

1. Regression equations for the adsorption of iodine and methylene blue have been obtained:

$$Ai_2 = 179.61 + 37.37X_3 - 10.63X_1X_2 + 26.88X_1X_3 - 7.13X_1^2 + \\ + 23.82X_2^2 - 7.13X_3^2,$$

$$F_p = 0.39; F_{tab} = 4.82;$$

$$A_{MB} = 680.79 - 40.67X_1 + 130.74X_2 + 60.00X_1X_3 + 57.00X_2X_3 + \\ + 53.28X_2^2 - 33.01X_3^2,$$

$$F_p = 1,17; F_{tab} = 4.82.$$

2. Regression equations have been obtained for Brunauer–Emmett–Teller and Barrett-Joyner-Halenda methods:

$$V_{BET} = 0.36 + 0.15X_3 - 0.06X_1X_2 + 0.07X_1X_3,$$

$$F_p = 3.81; F_{tab} = 4.72;$$

$$V_{BJH} = 0.08 + 0.07X_3 + 0.03X_1X_3 + 0.05X_3^2,$$

$$F_p = 4.17; F_{tab} = 4.72.$$

3. It has been established that the formation of the specified properties is influenced jointly by the pyrolysis temperature and the activating agent dosage.

4. According to the results of the experiment, for the synthesis of adsorbents from sludge-lignin, the recommended pyrolysis temperature is 700 °C and the activating agent dosage is 180 %. The advantage of this technology is the low consumption of NaOH for the activation of carbon material compared to sorbents from hydrolysis or sulphate lignin.

5. These sorbents are applicable for the selective extraction of radionuclides from liquid radioactive waste.

6. On this basis, adsorbents obtained during the thermochemical activation of sludge-lignin are effective for the selective extraction of radionuclides with an atomic radius of 140 to 215 pm from an aqueous medium, including strontium, niobium and manganese.

REFERENCES

1. Bedmohata M.A., Chaudhari A.R., Singh S.P., Choudhary M.D. Adsorption Capacity of Activated Carbon Prepared by Chemical Activation of Lignin for the Removal of Methylene Blue Dye. *International Journal of Advanced Research in Chemical Science (IJARCS)*, 2015, vol. 2, iss. 8, pp. 1–13.

2. Beletskaya M.G., Bogdanovich N.I., Makarevich N.A. *Carbon Adsorbent Technology: Physico-Chemical Analysis of Activated Carbons*. Arkhangelsk, Northern (Arctic) Federal University Publ., 2015. 96 p. (In Russ.).

3. Bogdanovich N.I. Pyrolysis of Technical Lignins. *Lesnoy Zhurnal* = Russian Forestry Journal, 1998, no. 2–3, pp. 120–132. (In Russ.).

4. Bogdanovich N.I., Kuznetsova L.N., Dobele G.V. New Reagents of Thermochemical Activation of Carbon Materials in the Synthesis of Adsorbents. *Carbon Adsorbents*: Proceedings of the 2nd International Seminar. Kemerovo, Institute of Coal and Coal Chemistry of the Siberian Branch of the Russian Academy of Sciences Publ., 2000, pp. 16–18. (In Russ.).

5. Celik A., Demirbaş A. Removal of Heavy Metal Ions from Aqueous Solutions via Adsorption onto Modified Lignin from Pulping Wastes. *Energy Sources*, 2005, vol. 27, iss. 12, pp. 1167–1177. https://doi.org/10.1080/00908310490479583

6. Chernysheva E.A., Nakhanovich V.S., Zajtseva A.A., Russavskaya N.V. Technology and Equipment for Obtaining Sulfur-Containing Sorbents Based on Lignin. *Collection of Scientific Papers of the Angarsk State Technical University*, 2016, no. 1, pp. 76–80. (In Russ.).

7. Chistyakov A.V., Tsodikov M.V. Methods for Preparing Carbon Sorbents from Lignin (Review). *Russian Journal of Applied Chemistry*, 2018, vol. 91, pp. 1090–1105. https://doi.org/10.1134/S1070427218070054

8. Elnakar H., Buchanan I.D. Pulp and Paper Mill Effluent Management. *Water Environment Research*, 2019, vol. 91, iss. 10, pp. 1069–1071. https://doi.org/10.1002/wer.1179

9. *Irkutsk National Research Technical University. INRTU Scientists Will Present Several Waste Disposal Technologies from the Baikal Central Processing Plant at the International Ecological and Water Forum*. Avaialble at: https://www.istu.edu/novosti/pub/45665 (accessed 5.08.24). (In Russ.).

10. Khorokhordin A.M., Rudakov O.Ya., Perzev V.T., Cherepakhina R.G., Rudakov O.B. Application of Slime-Lignin with Slaked Lime as an Organomineral Additive in Cement. *Khimiya, fizika i mekhanika materialov*, 2021, no. 2(29), pp. 89–96. (In Russ.).

11. Lainer Yu.A., Malkov G.A., Tuzhilin A.S., Perekhoda S.P., Vetchinkina T.N. Prospects of Aluminum-Containing Waste Integrated Treatment with Production of Alumina, Coagulants and Construction Materials. *Ekologiya i promyshlennost' Rossii* = Ecology and Industry of Russia, 2013, no. 4, pp. 10–15. (In Russ.). https://doi.org/10.18412/1816-0395-2013-4-10-15

12. Lityaeva Z.A., Gavrilov S.N. *Combined Humate-Containing Reagent for Drilling Fluids*. Patent RF no. 208751, 1997. (In Russ.).

13. Loginova (Kokina) E.S., Boykova T.E., Bogdanovich N.I., Vorontsov K.B., Adsorption of Cobalt Isotope from Liquid Radioactive Waste by Carbon Nanostructured Materials of Thermochemical Activation of Sludge-Lignin. *Bezopasnost' i okhrana truda v lesozagotovitel'nom i derevoobrabatyvayushchem proizvodstvakh* = Occupational Health and Safety in Logging and Woodworking Industries, 2024, no. 3. https://doi.org/10.33920/pro-5-2403-04

14. Malnik V.V., Yamamuro M., Tomberg I.V., Molozhnikova E.V., Bukin Yu.S., Timoshkin O.A. Lacustrine, Wastewater, Interstitial and Fluvial Water Quality in the Southern Lake Baikal Region. *Journal of Water & Health*, 2022, vol. 20, iss. 1, pp. 23–40. https://doi.org/10.2166/wh.2021.064

15. *Methodology for Measuring the Activity of Gamma-Emitting Nuclides in Counting Samples Using a Semiconducting Spectrometer*. Certificate no. 582/04 on Certification Issued by D.I. Mendeleyev Institute for Metrology, 25.10.2004. (In Russ.).

16. Sedova E.L., Vorontsov K.B., Burkova S.A. Influence of Coagulation Treatment on the Efficiency of Lignin Containing Wastewater Purification. *Lesnoy Zhurnal* = Russian Forestry Journal, 2019, no. 4, pp. 159–167. (In Russ.). https://doi.org/10.17238/issn0536-1036.2019.4.159

17. Suhas, Carrott P.J.M., Ribeiro Carrott M.M.L. Lignin – from Natural Adsorbent to Activated Carbon: A Review. *Bioresource Technology*, 2007, vol. 98, iss. 12, pp. 2301–2312. https://doi.org/10.1016/j.biortech.2006.08.008

18. Thompson G., Swain J., Kay M., Forster C.F. The Treatment of Pulp and Paper Mill Effluent: A Review. *Bioresource Technology*, 2001, vol. 77, iss. 3, pp. 275–286. https://doi.org/10.1016/s0960-8524(00)00060-2

19. Timofeeva S.S. Vermicomposting of Technical Waste and Their Biological Activity. *Environmental Safety of the East Siberian Region*: Proceedings of the All-Russian Scientific and Practical Conference. Irkutsk, 2003, pp. 17–21. (In Russ.).

20. Vorontsov K.B., Bogdanovich N.I., Sedova E.L., Solovyova P.V. Formation of Adsorption Properties of Carbon Nanostructured Materials by Thermochemical Activation of Sludge-Lignin. *Lesnoy Zhurnal* = Russian Forestry Journal, 2021, no. 4, pp. 181–188. (In Russ.). https://doi.org/10.37482/0536-1036-2021-4-181-189

Конфликт интересов: Авторы заявляют об отсутствии конфликта интересов
Conflict of interest: The authors declare that there is no conflict of interest

Вклад авторов: Все авторы в равной доле участвовали в написании статьи
Authors' Contribution: All authors contributed equally to the writing of the article