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REMOVAL OF METHYLENE BLUE FROM WATER BY NiO-MODIFIED SILICA GEL

The objects of the study are sorption materials based on commercial silica gel and nickel (II) oxide with different mass ratios of NiO to SiO₂: 1:1 and 0.5:1. To obtain such materials, expensive reagents and complex synthesis schemes are not required. In addition, they are distinguished by chemical stability, controlled morphology and have a significant number of reactive functional groups, which contributes to high adsorption capacity for various types of contaminants.

The morphology of composite sorbents was studied using the electron microscopy method, the presence of a crystalline phase of nickel oxide on the amorphous surface of silica gel was investigated by X-ray phase analysis, and the successful application of a layer of nickel-containing compounds was confirmed by infrared spectroscopy.

The main parameters of the mesoporous structure of the samples were determined by the method of low-temperature nitrogen adsorption/desorption. It was found that with an increase in the amount of the deposited oxide layer, the specific surface area and pore volume of the obtained sorbents decrease by 1.5–2 times compared to the original silica gel.

The physicochemical features of the extraction of methylene blue dye by nickel-containing composites based on silica gel were studied. It was found that modification of the SiO₂ surface with nickel (II) oxide leads to an increase in the sorption capacity of materials in relation to cationic dyes. It was shown that the highest sorption capacity is possessed by a sample with a mass ratio of NiO to SiO₂ equal to 0.5:1. The maximum sorption value is 21 mg/g, which is almost 2 times higher than that for the original silica gel. The adsorption kinetics is adequately described by pseudo-first and pseudo-second order models, which indicates a high affinity of methylene blue with the surface of such samples.

The results obtained indicate that the obtained sorption materials based on commercial silica gel and nickel (II) oxide can be used in the purification of water contaminated with organic cationic dyes.

Keywords: adsorption, organic dyes, modification, nickel (II) oxide, water purification, silica gel.

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1. Introduction

The demand for fresh water is constantly increasing along with the increase in population and the improvement of living standards. The reserves of clean fresh water, which are provided by both surface and underground water resources, are decreasing due to their pollution by inorganic and organic substances and limited availability. One way to solve this problem is to treat industrial wastewater from toxic pollutants to a level that allows them to be discharged into the natural aquatic environment.

Many industries, such as textile, cosmetic, paper, printing, chemical, etc., use various synthetic dyes to dye their products. As a result, wastewater is formed, which is a potential hazard to the environment and poses a serious threat to human health and other living organisms [1]. Most organic dyes are toxic, have carcinogenic and mutagenic effects on living organisms and negatively affect the photosynthesis processes of aquatic biota [2–4]. Due to their limited biodegradability, organic dyes are mainly removed from the aquatic environment. Various technologies are used for this purpose, including ion exchange, chemical precipitation, biosorption, filtration, reverse osmosis, and adsorption [5, 6].

Adsorption has attracted much attention from researchers due to its high efficiency, low cost, and ease of use. The most important part of the adsorption process is the selection of adsorbents. Various adsorbents are proposed for the effective removal of dyes. Thus, the most common adsorption material is activated carbon [7], which is characterized by a large surface area, high chemical stability, and excellent adsorption capacity. Sorption materials based on activated carbon effectively adsorb a wide range of cationic and anionic dyes from water [6]. However, the costs of production and regeneration are still relatively high, which limits its widespread use. Therefore, researchers have drawn attention to other adsorbents that are equally effective at a much lower cost. These include adsorbents obtained from agricultural waste (rice husk, coconut shells, sawdust, etc.) [8, 9]. For example, cationized cellulose has been obtained from rice husk, which exhibits a high adsorption capacity for the adsorption of anionic dyes [10]. A sorbent based on biochar obtained by pyrolysis of sugarcane processing waste activated by alkali effectively removes cationic dyes from water [11]. These methods provide valuable ideas for the development of inexpensive and effective adsorbents, but they require a large amount of natural raw materials, which limits their

widespread use. At the same time, their adsorption capacity significantly depends on the synthesis process and the type of dye.

Among inorganic materials, silicate-based sorbents can be included in a separate group. They are promising adsorbents for the removal of dyes due to their high chemical and mechanical stability, low cost, availability and structure, which allows modifying their surface by various methods to increase reactivity [12, 13]. It is known that metal oxides exhibit adsorption and photocatalytic ability to organic pollutants, including synthetic dyes [14–16]. There are also works that present the results of effective adsorption of dyes by composite materials based on metal oxides and silicates, including using amorphous forms of silica [17, 18].

Therefore, the aim of this study is to obtain an adsorbent based on commercial silica gel with a nickel oxide layer applied for the removal of the organic dye methylene blue from aqueous solutions. Studying the morphology, structural and sorption characteristics, and physicochemical features of the obtained materials will allow for their targeted synthesis, which will contribute to obtaining effective materials with unique properties.

2. Materials and Methods

2.1. Materials

To obtain sorption materials, the following were used: commercial silica gel (SiO_2) with a particle size of 230–400 mesh, nickel nitrate ($\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), 65 % nitric acid (HNO_3) and sucrose (99.9 %), which were purchased from Sigma-Aldrich (USA).

2.2. Instruments and analytic methods

The morphology of the samples and the elemental composition of the composites were studied using Nova Nano SEM450 scanning electron microscope (USA). The crystal structure of the modified materials was analyzed on D8 Advance X-ray diffractometer (Germany). The presence of functional groups on the surface of the sorbents was studied using an infrared spectrometer model Bruker Vertex 70 (Germany). The parameters of the porous struc-

ture of the synthesized samples were determined by the method of low-temperature nitrogen adsorption-desorption. The obtained data were processed using the specialized software Quantachrome NovaWin version 11.04. The specific surface area (S_{BET} , m^2/g) was calculated by the multi-point Brunauer-Emmett-Teller method, and the total pore volume (V_{Σ} , cm^3/g) was determined by the maximum adsorbed volume of nitrogen at a relative $p/p_0 \approx 1$ (0.99).

The adsorption capacity of the obtained samples was evaluated on model solutions contaminated with methylene blue. The study was carried out at room temperature under static conditions and continuous shaking on a shaker for 1 hour. A 0.1 g sample of the studied material was used for the sorption experiment. The volume of the solution was 50 cm^3 . After establishing the adsorption equilibrium, the liquid phase was separated from the solid phase by centrifugation and the equilibrium concentration of the dye in the aqueous phase was determined spectrophotometrically. The optical density of the solutions was determined on UNICO-UV 2100 spectrophotometer (USA) at $\lambda = 665$ nm and an absorbing layer thickness of 1 cm. The adsorption value (a , mg/g) of methylene blue was calculated by the formula:

$$a = \frac{(C_{in} - C_e) \cdot V}{m}, \quad (1)$$

where C_{in} and C_e – the initial and equilibrium concentrations of methylene blue (mg/dm^3); V – the volume of the solution (dm^3); m is the mass of the adsorbent (g).

2.3. Preparation of silica gel modified with nickel oxide

Sorption materials were synthesized according to the modified method described in [15]. Fig. 1 schematically depicts the process of sorbent synthesis.

First, 2 wt. % aqueous suspension of SiO_2 was prepared. Then, while continuing to stir with a magnetic stirrer, the calculated amount of $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and sucrose was added sequentially. The mass ratio of NiO to SiO_2 was 1:1 and 0.5:1. After complete dissolution of the reagents, several cm^3 of HNO_3 were added and the mixture was stirred for 30 minutes at room temperature.

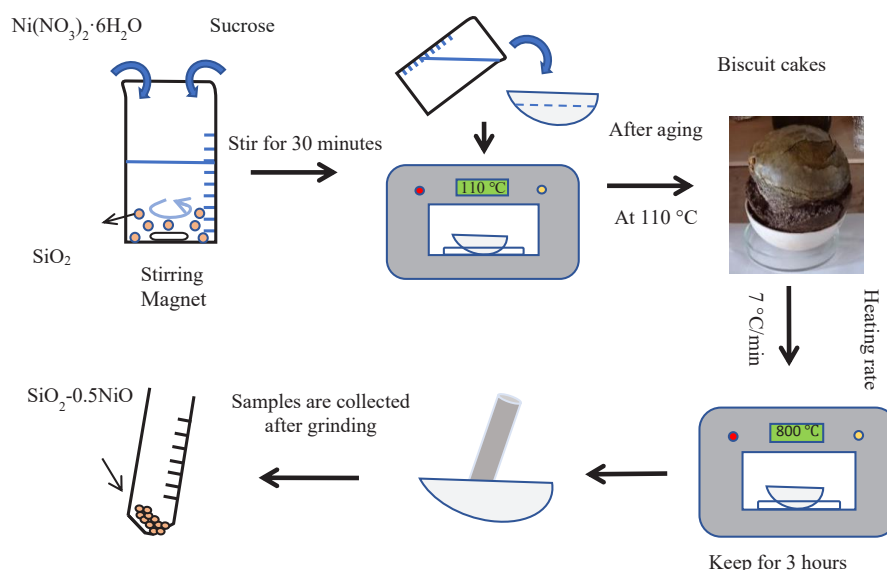


Fig. 1. Scheme of preparation of a sorbent based on silica gel modified with nickel oxide

The next stage of synthesis consisted of several successive stages of temperature treatment at 110 °C, 250 °C and 800 °C. After holding at 110 °C, the samples resembled biscuit cakes in appearance. The temperature of 800 °C corresponds to the thermolysis process in air, which was carried out at a heating rate of 7 °C/min and holding at the maximum temperature for 3 hours. For further studies, the fired samples were crushed and sieved to obtain a fraction ≤ 0.315 mm.

3. Results and Discussion

Fig. 2 shows images of the microstructure of commercial SiO_2 and synthesized samples $\text{SiO}_2\text{-}0.5\text{NiO}$ and $\text{SiO}_2\text{-NiO}$.

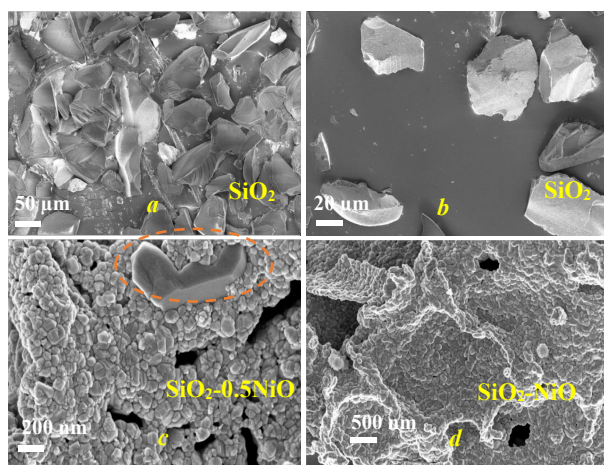


Fig. 2. Characterization of the obtained materials:
a, b – SEM images of SiO_2 ; *c* – SEM images of $\text{SiO}_2\text{-}0.5\text{NiO}$;
d – SEM image of $\text{SiO}_2\text{-NiO}$

It can be seen that the particles of the initial silica gel do not stick together and have an irregular shape (Fig. 2, *a, b*). After modifying its surface with nickel oxide ($\text{SiO}_2\text{-}0.5\text{NiO}$ sample), the formation of a NiO layer is observed (Fig. 2, *c*). The presence of this layer is possible due to the fact that SiO_2 and NiO are charged oppositely – negatively and positively, respectively, which allows nickel oxide particles to remain on the SiO_2 surface due to the attraction of charges [17]. It can also be seen that not the entire surface of the silica gel is completely covered with nickel oxide (Fig. 2, *c*, highlighted in orange), due to which both silica gel and nickel oxide can participate in the dye adsorption process. With an increase in the amount of deposited NiO ($\text{SiO}_2\text{-NiO}$ sample in Fig. 2, *d*) it is possible to observe an almost completely covered SiO_2 surface, which indicates that further increasing the amount of nickel oxide is no longer of practical importance.

Fig. 3 shows the elemental analysis of the $\text{SiO}_2\text{-}0.5\text{NiO}$ sample. It can be seen that the element Ni is evenly distributed on the surface of the material, which indicates that nickel oxide is evenly deposited on the surface of the silica gel – silica composite material filled with nickel oxide.

In addition, all three elements Si, O are also evenly distributed in the composite sorption material, which further proves its successful synthesis.

To obtain information about the functional groups that are on the surface of the original silica gel and what changes occur to the surface during modification, IR spectra of the samples were obtained, which are presented in Fig. 4.

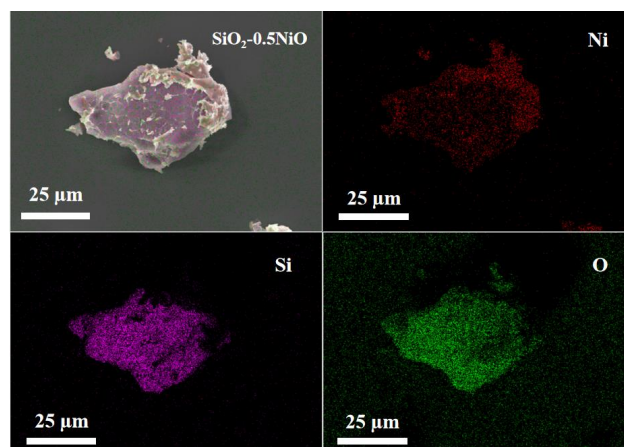


Fig. 3. EDS mapping characterization of $\text{SiO}_2\text{-}0.5\text{NiO}$

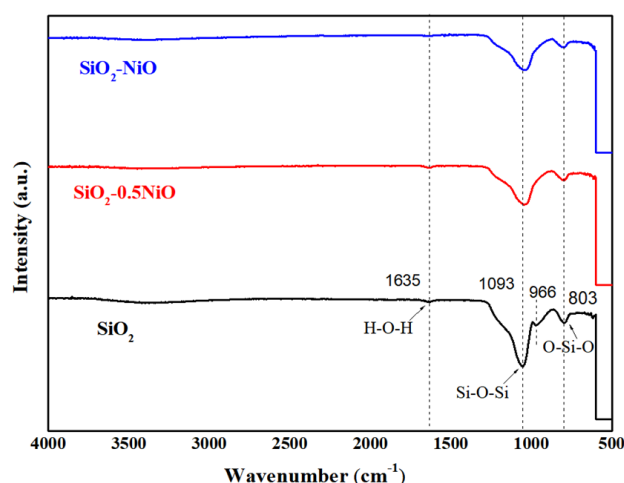


Fig. 4. FTIR images of the obtained materials

It was found that all three materials are characterized by a weak peak at 1635 cm^{-1} , which is due to the vibrations of hydroxyl groups (H-O-H) [19]. In addition, the peaks shown at 1093 cm^{-1} and 803 cm^{-1} , on the other hand, correspond to asymmetric vibrations of Si-O-Si bonds [20]. Only in the IR spectrum of silica gel, a silica-specific peak of Si-OH bonds at 966 cm^{-1} is observed. For the composite samples $\text{SiO}_2\text{-}0.5\text{NiO}$ and $\text{SiO}_2\text{-NiO}$, the intensity of this peak weakens with an increase in the amount of deposited NiO, which confirms the successful completion of the modification [21]. In addition, the presence of a crystalline phase of nickel oxide on the surface of silica gel is confirmed by X-ray phase analysis. For the $\text{SiO}_2\text{-}0.5\text{NiO}$ and $\text{SiO}_2\text{-NiO}$ samples, characteristic peaks for NiO are observed at $2\theta = 37^\circ, 43^\circ, 62^\circ, 75^\circ$ and 79° , corresponding to the (222), (400), (440), (622), (444) planes, respectively (JCPDS database map No. 89-5881) and a broad peak at $2\theta \approx 22^\circ$ characteristic of SiO_2 in the amorphous phase [22].

Nitrogen adsorption-desorption isotherms on the original silica gel and modified samples belong to type IV isotherms according to the IUPAC classification, which is typical for materials with a mesoporous structure and a pore size in a narrow range, about 2.5–3 nm. It was found that after applying a nickel oxide layer to silica gel, the specific surface area and pore volume decrease significantly. Thus, SiO_2 has a specific surface area of $411\text{ m}^2/\text{g}$ and a total pore

volume of $0.746 \text{ cm}^3/\text{g}$. The same values for $\text{SiO}_2\text{-}0.5\text{NiO}$ and $\text{SiO}_2\text{-NiO}$ are $256 \text{ m}^2/\text{g}$ and $0.387 \text{ cm}^3/\text{g}$ and $186 \text{ m}^2/\text{g}$ and $0.290 \text{ cm}^3/\text{g}$, respectively, which indicates that the pores are partially blocked by NiO particles or NiO agglomerates are formed on the pore walls [22].

Fig. 5 shows the dependences of the sorption values of methylene blue on the time of contact with the sorption materials.

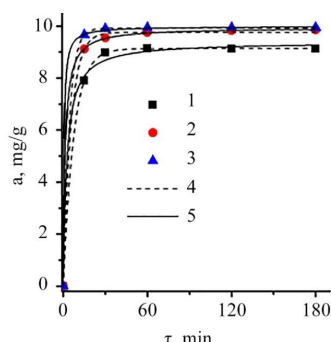


Fig. 5. Adsorption kinetics of methylene blue adsorption by the obtained materials: 1 – SiO_2 ; 2 – $\text{SiO}_2\text{-NiO}$ (1:1); 3 – $\text{SiO}_2\text{-NiO}$ (1:0.5); 4 – pseudo-first-order; 5 – pseudo-second-order

The results indicate that at an initial dye concentration of 20 mg/dm^3 all the studied materials adsorb methylene blue cations quite quickly. The equilibrium state occurs practically within 15–30 minutes, and 1 hour is quite sufficient for adsorption experiments. The analysis of kinetic curves was carried out using pseudo-first and pseudo-second order kinetic models. Table 1 shows the calculated parameters of the corresponding equations. The obtained data show that the correlation coefficients of all materials have a very high correspondence to the kinetic models of both orders and are close to 1 ($R^2 > 0.99$).

Fig. 6 shows the adsorption isotherms of methylene blue on the original SiO_2 and modified samples based on it. The results obtained indicate that the sorption capacity of SiO_2 with respect to dye ions is somewhat lower than on composite sorbents. It is found that all materials effectively adsorb dye cations from the solution at low initial concentrations, which is due to the presence of a sufficient number of active adsorption centers on the surface.

With an increase in the dye concentration in the solution, the surface of the sorbents gradually becomes saturated and at a certain content of the pollutant in the solution, the sorption value no longer increases. It is shown that the maximum adsorption capacity of silica composites after applying NiO increases compared to the original silica, and the efficiency of $\text{SiO}_2\text{-NiO}$ (1:0.5) is higher than $\text{SiO}_2\text{-NiO}$ (1:1).

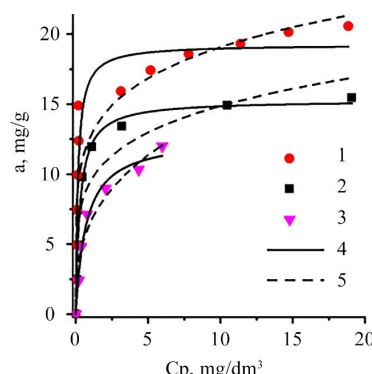


Fig. 6. Adsorption isotherms of methylene blue by the investigated samples: 1 – $\text{SiO}_2\text{-NiO}$ (1:0.5); 2 – $\text{SiO}_2\text{-NiO}$ (1:1); 3 – SiO_2 ; 4 – Langmuir model; Freundlich model

The experimental data were tested using Langmuir and Freundlich models, respectively, and the equations for the two isotherm models are expressed as follows:

– Langmuir:

$$\frac{C_e}{q_e} = \frac{1}{q_m K_L} + \frac{C_e}{q_m}; \quad (2)$$

– Freundlich:

$$\ln q_e = \frac{1}{n} \ln C_e + \ln K_F, \quad (3)$$

where $C_e \text{ (mg}\cdot\text{l}^{-1}\text{)}$ – the equilibrium concentration of the heavy metal ions; $q_e \text{ (mg}\cdot\text{g}^{-1}\text{)}$ – the equilibrium adsorption capacity of the heavy metal ions adsorbed on the adsorbent; $q_m \text{ (mg}\cdot\text{g}^{-1}\text{)}$ – the maximum adsorption capacity of the adsorbents; $K_L \text{ (l}\cdot\text{mg}^{-1}\text{)}$ and $K_F \text{ (mg}\cdot\text{g}^{-1}\text{)}$ – the Langmuir and Freundlich constants, respectively; n – the constant related to the heterogeneity of the adsorbent sites [23].

Table 1

Kinetic parameters adsorption of methylene blue on the obtained materials

Sample	Pseudo-first-order			Pseudo-second-order		
	$q_e \text{ (mg}\cdot\text{g}^{-1}\text{)}$	$K_1 \text{ (min}^{-1}\text{)}$	R^2	$q_e \text{ (mg}\cdot\text{g}^{-1}\text{)}$	$K_2 \text{ (g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}\text{)}$	R^2
SiO_2	9.1310	0.1338	0.999	9.394	0.0435	0.997
$\text{SiO}_2\text{-NiO}$ (1:1)	9.7568	0.1796	0.999	9.940	0.0759	0.999
$\text{SiO}_2\text{-NiO}$ (1:0.5)	9.9248	0.2388	0.999	9.992	0.2068	0.999

Fitting parameters for methylene blue adsorption removal isotherms for the investigated samples

Table 2

Sample	Langmuir			Freundlich		
	$q_m \text{ (mg}\cdot\text{g}^{-1}\text{)}$	$K_L \text{ (l}\cdot\text{mg}^{-1}\text{)}$	R^2	$K_F \text{ (mg}\cdot\text{g}^{-1}\text{)}$	n	R^2
SiO_2	12.636	1.426	0.983	6.528	2.91	0.959
$\text{SiO}_2\text{-NiO}$ (1:0.5)	19.259	6.613	0.876	12.670	5.63	0.836
$\text{SiO}_2\text{-NiO}$ (1:1)	15.286	3.459	0.974	9.458	5.09	0.869

Research limitations. To implement the obtained results in practice, it is necessary to conduct research into the main physicochemical features of the removal of organic dyes from industrial wastewater. To scale up the sorption technology using the materials obtained in the work, a simple and affordable method for the synthesis of granular adsorbents should be developed, which will significantly improve the manufacturability of the purification process.

The conditions of martial law in Ukraine affected the conduct of these studies, because obtaining scientific results was complicated by power outages and practically stopped when receiving the "Air Alert" signal. In addition, the purchase of reagents from abroad and the implementation of instrumental research methods required funding, which has significantly decreased since the beginning of the full-scale invasion of Russia into the territory of our state.

In further research, more attention should be paid to the production of granular adsorption materials based on available aluminosilicate raw materials and the study of the features of the removal of both cationic and anionic organic dyes from real wastewater, which may contain a complex mixture of pollutants. For this, it is necessary to improve the structural and sorption characteristics and selectivity of the obtained adsorbents by applying a mixture of various metal oxides to the inorganic matrix, which will significantly increase the adsorption capacity of such materials. It is also advisable to investigate the possibility of regenerating the spent material for the purpose of its reuse.

4. Conclusions

Sorption materials based on commercial silica gel and nickel oxide with different mass ratios of components were obtained. Analysis of structural and sorption characteristics showed that the obtained samples retained the mesoporous structure of the original matrix after applying the modifier layer. At the same time, the specific surface area and average pore radius decreased slightly compared to the original sample. It was found that the removal of methylene blue from the solution by the synthesized materials occurs quite quickly, and the maximum adsorption capacity is possessed by $\text{SiO}_2\text{-NiO}$ (1:0.5). However, the issues of effective phase separation after sorption and the possibility of regeneration of the spent material remain unresolved.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

- Natarajan, S., Bajaj, H. C., Tayade, R. J. (2018). Recent advances based on the synergetic effect of adsorption for removal of dyes from waste water using photocatalytic process. *Journal of Environmental Sciences*, 65, 201–222. <https://doi.org/10.1016/j.jes.2017.03.011>
- Saruchi, Kumar, V., Dhama, J. K., Rehani, V., Singh, M. (2022). Synthesis and characterization of Aloe-vera-poly(acrylic acid)-Cu-Ni-bionanocomposite: its evaluation as removal of carcinogenic dye malachite green. *Journal of Polymer Research*, 29 (2). <https://doi.org/10.1007/s10965-022-02898-7>
- Verma, N., Chundawat, T. S., Chandra, H., Vaya, D. (2023). An efficient time reductive photocatalytic degradation of carcinogenic dyes by $\text{TiO}_2\text{-GO}$ nanocomposite. *Materials Research Bulletin*, 158, 112043. <https://doi.org/10.1016/j.materresbull.2022.112043>
- Kyzas, G., Fu, J., Matis, K. (2013). The Change from Past to Future for Adsorbent Materials in Treatment of Dyeing Wastewaters. *Materials*, 6 (11), 5131–5158. <https://doi.org/10.3390/ma6115131>
- Ahmad, A., Mohd-Setapar, S. H., Chuong, C. S., Khattoon, A., Wani, W. A., Kumar, R., Rafatullah, M. (2015). Recent advances in new generation dye removal technologies: novel search for approaches to reprocess wastewater. *RSC Advances*, 5 (39), 30801–30818. <https://doi.org/10.1039/c4ra16959j>
- Yagub, M. T., Sen, T. K., Afroze, S., Ang, H. M. (2014). Dye and its removal from aqueous solution by adsorption: A review. *Advances in Colloid and Interface Science*, 209, 172–184. <https://doi.org/10.1016/j.cis.2014.04.002>
- Heidarinejad, Z., Dehghani, M. H., Heidari, M., Javedan, G., Ali, I., Sillanpää, M. (2020). Methods for preparation and activation of activated carbon: a review. *Environmental Chemistry Letters*, 18 (2), 393–415. <https://doi.org/10.1007/s10311-019-00955-0>
- Paul Nayagam, J. O., Prasanna, K. (2022). Utilization of shell-based agricultural waste adsorbents for removing dyes: A review. *Chemosphere*, 291, 132737. <https://doi.org/10.1016/j.chemosphere.2021.132737>
- Hambisa, A. A., Regasa, M. B., Ejigu, H. G., Senbeto, C. B. (2022). Adsorption studies of methyl orange dye removal from aqueous solution using Anchote peel-based agricultural waste adsorbent. *Applied Water Science*, 13 (1). <https://doi.org/10.1007/s13201-022-01832-y>
- Jiang, Z., Hu, D. (2019). Molecular mechanism of anionic dyes adsorption on cationized rice husk cellulose from agricultural wastes. *Journal of Molecular Liquids*, 276, 105–114. <https://doi.org/10.1016/j.jmolliq.2018.11.153>
- Moharm, A. E., El Naeem, G. A., Soliman, H. M. A., Abdelhamid, A. I., El-Bardan, A. A., Kassem, T. S. et al. (2022). Fabrication and Characterization of Effective Biochar Biosorbent Derived from Agricultural Waste to Remove Cationic Dyes from Wastewater. *Polymers*, 14 (13), 2587. <https://doi.org/10.3390/polym14132587>
- Samantray, J., Anand, A., Dash, B., Ghosh, M. K., Behera, A. K. (2022). Silicate minerals – Potential source of potash – A review. *Minerals Engineering*, 179, 107463. <https://doi.org/10.1016/j.mineng.2022.107463>
- Li, H., Chen, X., Shen, D., Wu, F., Pleixats, R., Pan, J. (2021). Functionalized silica nanoparticles: classification, synthetic approaches and recent advances in adsorption applications. *Nanoscale*, 13 (38), 15998–16016. <https://doi.org/10.1039/d1nr04048k>
- Goswami, B., Mahanta, D. (2019). Polyaniline coated nickel oxide nanoparticles for the removal of phenolic compounds: Equilibrium, kinetics and thermodynamic studies. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 582, 123843. <https://doi.org/10.1016/j.colsurfa.2019.123843>
- El-Qanni, A., Nassar, N. N., Vitale, G. (2017). Experimental and computational modeling studies on silica-embedded NiO/MgO nanoparticles for adsorptive removal of organic pollutants from wastewater. *RSC Advances*, 7 (23), 14021–14038. <https://doi.org/10.1039/c7ra00615b>
- Mustafa, S., Mahmood, F., Shafqat, U., Hussain, S., Shahid, M., Batool, F. et al. (2023). The Biosynthesis of Nickel Oxide Nanoparticles: An Eco-Friendly Approach for Azo Dye Decolorization and Industrial Wastewater Treatment. *Sustainability*, 15 (20), 14965. <https://doi.org/10.3390/su152014965>

17. Rubab, R., Ali, S., Rehman, A. U., Khan, S. A., Khan, A. M. (2021). Templated synthesis of NiO/SiO₂ nanocomposite for dye removal applications: Adsorption kinetics and thermodynamic properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 615, 126253. <https://doi.org/10.1016/j.colsurfa.2021.126253>
 18. El Ghmari, B., Farah, H., Ech-Chahad, A. (2023). Biosynthesis, Characterization of Nickel (II) Oxide Nanoparticles NiO and their High-Efficient Photocatalytic Application. *International Journal of Nanoscience and Nanotechnology*, 19 (3), 135–147. <https://doi.org/10.22034/ijnn.2023.560608.2262>
 19. Rebelo, Q. H. F., Ferreira, C. S., Santos, P. L., Bonacin, J. A., Passos, R. R., Pocrifka, L. A., Paula, M. M. S. (2018). Synthesis and characterization of a nanocomposite NiO/SiO₂ from a sustainable source of SiO₂. *Particulate Science and Technology*, 37 (8), 911–915. <https://doi.org/10.1080/02726351.2018.1455781>
 20. Ferreira, C. S., Santos, P. L., Bonacin, J. A., Passos, R. R., Pocrifka, L. A. (2015). Rice Husk Reuse in the Preparation of SnO₂/SiO₂ Nanocomposite. *Materials Research*, 18 (3), 639–643. <https://doi.org/10.1590/1516-1439.009015>
 21. Murashkevich, A. N., Lavitskaya, A. S., Barannikova, T. I., Zharskii, I. M. (2008). Infrared absorption spectra and structure of TiO₂-SiO₂ composites. *Journal of Applied Spectroscopy*, 75 (5), 730–734. <https://doi.org/10.1007/s10812-008-9097-3>
 22. Yu, J., Bondarieva, A., Tobilko, V., Pavlenko, V. (2024). Adsorption removal of cu (II) using ni-modified silica gel. water and water purification technologies. *Scientific and technical news*, 37 (3), 3–12. <https://doi.org/10.20535/2218-930032023302423>
 23. Andersson, K. I., Eriksson, M., Norgren, M. (2011). Removal of Lignin from Wastewater Generated by Mechanical Pulp Using Activated Charcoal and Fly Ash: Adsorption Isotherms and Thermodynamics. *Industrial & Engineering Chemistry Research*, 50 (13), 7722–7732. <https://doi.org/10.1021/ie200378s>
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