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Modified sorbents and their applications: A review

Zubayda Khaydarova[1,2,*], Nigora Chorieva[1], Xayit Turayev[3], Nazokat Muzaffarova[2], Kamoliddin Sharofiddinov[4], Maxliyo Abdullayeva[1], Gavkhar Melikulova[5]

[1]*Department of Chemical Engineering, Termez State University of Engineering and Agrotechnologies, P. O. Box: 190100, Termez, Uzbekistan.*
[2]*Department of Medical And Biological Chemistry, Tashkent State Medical University Termez Branch, P. O. Box: 190111, Termez, Uzbekistan.*
[3]*Faculty of Chemistry, Termez State University, P. O. Box: 190100, Termez, Uzbekistan.*
[4]*Department of Medical Psychology, Neurology and Psychiatry, Tashkent State Medical University Termez Branch, P. O. Box: 190111, Termez, Uzbekistan.*
[5]*Department of Chemical Technology of Inorganic Substances Tashkent Institute of Chemical Technology, Navoi 32, P. O. Box: 100011, Tashkent, Uzbekistan.*

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ABSTRACT

The discharge of heavy metal ions, persistent organic pollutants, and radioactive species into industrial effluents and wastewater poses a critical threat to environmental sustainability and public health. Conventional sorbent materials are often hindered by limited sorption capacity, poor selectivity, and insufficient reusability, which significantly restrict their large-scale applicability. To address these challenges, increasing research efforts have focused on the design of modified sorbents through chemical functionalization, polymer incorporation, and nanomaterial integration. These strategies have yielded sorbents with enhanced sorption performance, accelerated kinetics, tailored selectivity, and improved regeneration potential. This review provides a comprehensive overview of the synthesis approaches for modified sorbents, including chelating agent functionalization, polymer matrix hybridization, and nanoparticle-assisted modification. A growing body of evidence demonstrates the superior performance of modified sorbents in removing toxic heavy metal ions (Pb^{2+}, Cd^{2+}, Hg^{2+}), synthetic dyes, and organic pollutants from aqueous environments. Finally, the review highlights emerging challenges and future prospects, with particular emphasis on the development of multifunctional, environmentally benign, and intelligent ("smart") sorbent materials. Their potential for industrial-scale implementation and sustainable environmental remediation is discussed as a promising direction for future research.

1. Introduction

Sorbents (from the Latin *sorbens* — "absorbing") are solid or liquid materials capable of selectively capturing gases, vapors, or dissolved substances from their surroundings. In the current era of rapid industrial development, the practical application of scientific research has become more relevant than ever. Among the key products of chemical technology that are widely used across different industrial sectors, sorbents play a particularly important role.

They are employed for the purification and recovery of metals, the removal of heavy metals, organic compounds, and bacteria from wastewater, the capture of CO_2 under high temperatures, the formulation of low-temperature composites, sealants, and many other applications. Sorbents can exist in both solid and liquid states; common solid sorbents include activated carbon, silica gels, aluminosilicates, zeolites, and ion-exchange polymers [1]. The rapid growth of population, industrialization, and urbanization has drastically increased the global demand for clean water. Consequently, the search for alternative water sources, as well as the purification and recycling of wastewater, has become critical [2]. Among different approaches, layered aluminosilicate clay minerals have been

* Corresponding author E-mail: Input Corr. email address
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recognized as efficient adsorbents for wastewater treatment due to their technical stability, low cost, and environmental safety [3]. In recent studies, these minerals have been compared with activated carbon the most commonly used sorbent for the removal of specific metal ions from wastewater and gas streams.

Their natural ion-exchange properties are attributed to charge exchanges occurring between the interlayer spaces of the clay structure [4]. Montmorillonite, one of the most widely applied clay minerals, has been shown to possess relatively low charge density (0.2-0.6 eq./formula unit) [5].

Another significant breakthrough of the 20th century is the development of polymeric ion-exchange sorbents, which are now considered indispensable in multiple areas. Their applications span water softening, environmental remediation, wastewater treatment, hydrometallurgy, chromatography, biomolecular separation, and catalysis. These resins are typically composed of polymers covalently bonded to functional ligands. Such polymers can be engineered to possess a high concentration of adsorption-active sites and functional groups, enhancing their separation efficiency [6,7].

2. Novelty and significance of the review

This review presents a comprehensive and systematic analysis of modified sorbents, encompassing biosorbents, polymer-based sorbents, and nanomaterial-integrated sorbents, with a focus on their synthesis, functionalization, and application in environmental remediation. Unlike previous reviews, which often addressed individual sorbent categories or specific pollutants, this work integrates multidisciplinary insights to evaluate the performance, selectivity, and regeneration potential of sorbents for the simultaneous removal of heavy metals, dyes, and gaseous contaminants. In particular, the review highlights recent advances in hybrid and multifunctional sorbents, including intelligent “smart” materials, polymer composites, and eco-friendly biosorbents derived from agricultural waste, providing a unique perspective on sustainable and cost-effective solutions. Furthermore, emerging challenges and future directions are critically discussed, such as optimizing sorbent design for industrial-scale implementation, improving adsorption kinetics, and enhancing sorbent recyclability. By combining both fundamental mechanistic understanding and practical applications, this review offers a novel and integrative framework that has not been systematically addressed in the literature, thereby serving as a valuable reference for researchers and practitioners in environmental chemistry and material science. General information about sorbents and their mechanisms of action. Adsorption is one of the key processes used for pollutant removal. It occurs when atoms, ions, or molecules attach to the surface of a solid material. This is different from absorption, where the entire material volume takes up the substance. The efficiency of adsorption depends on several factors [8]. A high surface area offers more active sites for binding. Pore size distribution controls which molecules can enter and be captured. Surface chemistry, such as hydrophilic groups, affects the selectivity for different contaminants. In addition, molecular size and structure influence adsorption, with smaller and hydrophilic molecules being more easily adsorbed [9].

Several factors influence the efficiency of adsorption. Low solubility of contaminants usually makes them easier to capture. Electrostatic interactions between the adsorbent and pollutants also enhance the process. The pH of the solution can alter the charge and form of both the adsorbent and contaminant, affecting adsorption performance [10]. Temperature plays a role as well. Since adsorption is typically exothermic, higher temperatures often lower the adsorption capacity. Ionic strength can modify solubility, speciation, and surface charge, further influencing the process. Finally, longer contact time favors equilibrium, while effective mixing improves mass transfer and increases the interaction between contaminants and the adsorbent [11]. Adsorption is a key process in environmental remediation and industrial separations. It occurs through two main mechanisms: physisorption and chemisorption**.** Physisorption relies on weak forces such as van der Waals interactions, dipole–dipole attractions, and hydrogen bonding. It is non-specific, reversible, and favored at low temperatures and high pressures. Chemisorption forms stronger covalent or ionic bonds between the adsorbate and adsorbent. This process involves electron transfer and is usually irreversible without external energy [12]. The principles of adsorption also include: Ion exchange, where ions in solution are replaced by ions of similar charge on the adsorbent surface, guided by electrostatic forces. Surface complexation, where functional groups on the adsorbent form complexes with adsorbate molecules, enhancing both capacity and selectivity [13]. Precipitation is another adsorption principle, where insoluble compounds form on the adsorbent surface and play a vital role in purification. Understanding these mechanisms is important for designing efficient adsorption systems for water treatment, gas cleaning, catalysis, and pharmaceutical production. Each principle provides distinct benefits that affect the performance and sustainability of adsorption technologies in different applications [14]. Figure 1 shows how toxic metals are adsorbed from wastewater onto polymeric materials. Adsorption occurs through physical forces (van der Waals, hydrogen bonding) or

chemical bonds (covalent, electrostatic). The process is reversible, allowing desorption and reuse of adsorbents. Panel (b) illustrates monolayer adsorption, while panel (c) shows multilayer adsorption [15].

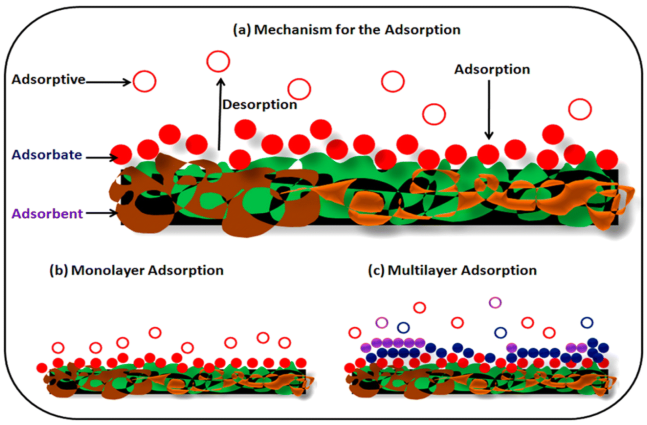

Fig. 1. (a) General mechanism for the adsorption, (b) monolayer adsorption, and (c) multilayer adsorption.

Physisorption, or physical adsorption, occurs through weak van der Waals forces between the adsorbate and the adsorbent surface. These include dispersion forces, dipole-dipole interactions, and hydrogen bonding, which are non-specific and weak. The process is usually reversible and favored at low temperatures and high pressures [16].

Chemisorption is a type of adsorption where strong covalent or ionic bonds form between the adsorbate and the adsorbent surface. It is stronger and more specific than physisorption and usually requires activation energy. Under normal conditions, chemisorption is often irreversible [17]. In some cases, both physisorption and chemisorption may occur together. The dominant mechanism depends on temperature, pressure, and the adsorbent's surface properties, which affect capacity and selectivity [18].

Ion exchange adsorption occurs when ions in solution are exchanged with ions on the adsorbent surface. This process relies on electrostatic interactions and the affinity of ions for charged sites. It is widely applied in water softening, purification, and soil remediation to remove heavy metals and radionuclides [19]. Surface complexation adsorption happens when hydrophilic groups on the adsorbent surface chemically interact with adsorbate molecules. This process may include ligand exchange, chelation, or coordination, depending on the surface chemistry of the adsorbent and the type of adsorbate [20]. Precipitation adsorption occurs when changes in solubility cause the adsorbate to form insoluble compounds that deposit on the adsorbent surface. This mechanism is especially important in wastewater treatment and separation processes [21]. Biosorption uses natural biological materials such as bacteria, algae, or plants to remove pollutants from water. The process includes ion exchange, surface complexation, and weak physical interactions. Functional groups like hydroxyl, carboxyl, and amino groups on the biomass surface play a key role in binding contaminants. Because it is low-cost and eco-friendly, biosorption is considered a sustainable method for environmental remediation [22]. Chiral adsorption is the selective binding of enantiomers, or mirror-image molecules, on chiral adsorbent surfaces. The process relies on specific interactions between the chiral centers of the adsorbent and the target molecules. This mechanism is widely applied in pharmaceuticals, fine chemicals, and food industries to separate or purify enantiomers. It plays a key role in ensuring the quality and effectiveness of chirally pure compounds [23]. Electrostatic adsorption takes place when charged ions or molecules are attracted to oppositely charged adsorbent surfaces. It is driven by coulombic forces between the charged species in solution and the functional groups on the adsorbent. This mechanism is widely applied in wastewater treatment, ion exchange chromatography, and other separation processes for selective removal of charged contaminants [24].

Figure 2 illustrates the multifaceted mechanisms involved in adsorption. The porous adsorbent structure interacts with ions and molecules through ion exchange, electrostatic attraction, van der Waals forces, coordination bonding, and precipitation. Reactive sites, exchangeable ions, and functional groups are represented with different colors to clarify their roles.

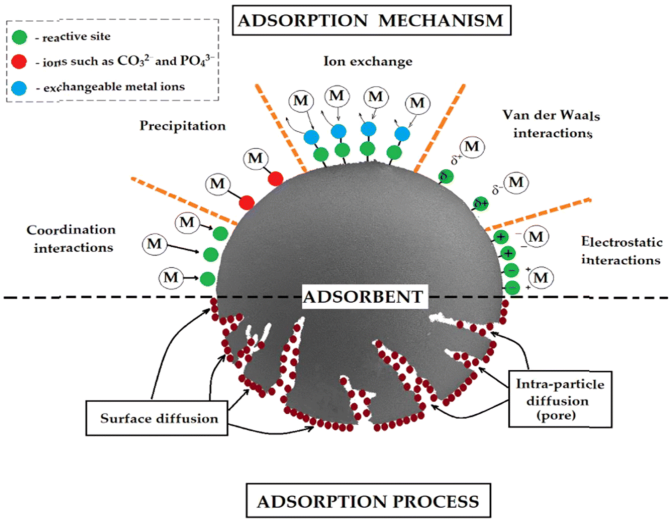

Fig. 2. Shows the proposed adsorption mechanism of ion removal.

The diagram also emphasizes two important transport pathways: surface diffusion, where ions migrate along the adsorbent surface, and intra-particle diffusion, where they penetrate the internal pores. Overall, the figure provides a clear overview of how surface interactions and internal diffusion collectively govern adsorption behavior [25].

3. Development and applications of modified sorbents.

In recent years, several modified types of ion-exchange resins-referred to as hybrid ion exchangers-have been developed to tackle complex environmental separation challenges. Their applications extend from the removal of trace contaminants and the desalination of brackish water, to nutrient recovery and even the direct capture of carbon dioxide from the atmosphere [26]. Tao Zhang *et al.* eutrophication and phosphorus scarcity drive the need for efficient phosphate removal from wastewater. Cerium-based sorbents are promising, but Ce (III) oxidation to Ce (IV) limits efficiency. To address this, a cerium-modified activated carbon (CeAC-A) was synthesized using ascorbic acid to stabilize Ce (III). The modified sorbent showed higher –OH groups (82.76%) and an adsorption capacity of 448.57 mg-P/g Ce, over four times greater than conventional CeAC. These results demonstrate that protective agents can enhance Ce-based sorbents, making CeAC-A a scalable and effective material for phosphate removal and environmental recovery [27].

A new method for developing sorbents based on surface-modified hydroxyapatite (HAp) nanoparticles is presented. These nanoparticles are designed for extracting nonionic surfactants. The approach relies on the oriented attachment (OA) mechanism, where small nanoparticles combine under hydrothermal conditions to form larger ones. Characterization results and quantum-chemical calculations suggest a possible mechanism for nanoparticle formation [28]. In another study, lignin sulfonate was obtained by treating corn stover, and then modified lignin sulfonate was obtained by hydrothermal method. Modified lignosulfonate adsorbent efficiency removes heavy metals in wastewater especially Cu^{2+} and Pb^{2+} [29]. Three cross-linked acrylic polymers were tested for Zn (II) removal from synthetic wastewater. These polymers were functionalized with triethylenetetramine (As30, As32) and acylated diethylenediamine (Cm26). Among the polymers, Cm26 had the highest sorption capacity (1135.77 mg g^{-1} at 293 K) (Figure 3**)** [30]. The polymers were synthesized by aminolysis of EA–AN–DVB copolymers with triethylenetetramine or ethylenediamine. Cm26 was further carboxymethylated. These polymers showed high ion-exchange ability and good stability, making them promising chelating sorbents for heavy metal removal. The removal of lead (Pb) from wastewater containing chelators is difficult because Pb-chelator complexes are highly stable and mobile. In this study, a biomass-based sorbent was developed: proline-incorporated dithiocarbamate-modified cellulose with epoxy cross-linking (DMC-Pro-Epo6). This sorbent was tested for Pb (II) removal under chelator-rich conditions. DMC-Pro-Epo6 showed excellent Pb (II) sorption performance. Even in the presence of a 100-fold excess of chelators and competing metal ions, the sorbent maintained high efficiency. Compared with commercial ion-selective sorbents, DMC-Pro-Epo6 achieved superior separation [31]. Unlike conventional treatment methods, this approach provides a simpler and more efficient way to separate metals and chelators from effluents. Even in the presence of strong chelators such as EDTA and DTPA, removal rates remained high (92-97 %). Therefore, DMC-Pro-Epo6 is a promising material for treating complex wastewaters, including those generated during soil-washing processes **(**Figure 4) [32].

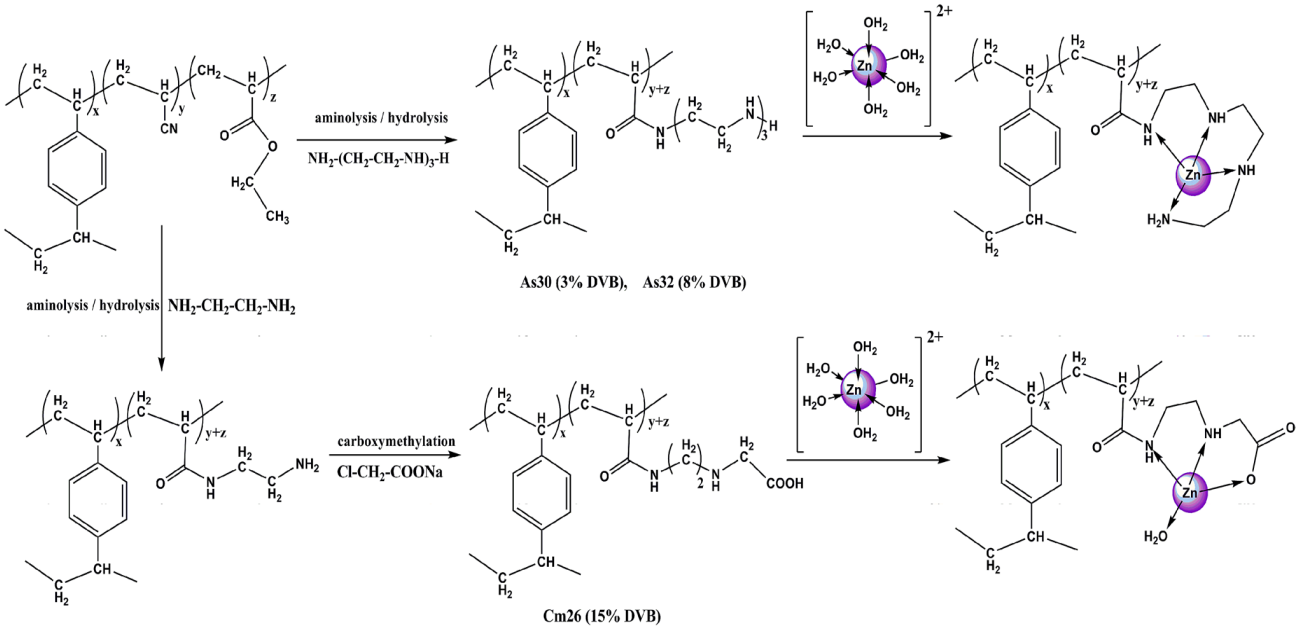

Fig. 3. Chemical reactions of AE-AN-DVB copolymers functionalization and a possible interaction of $Znaq^{2+}$ with functionalized acrylic copolymers.

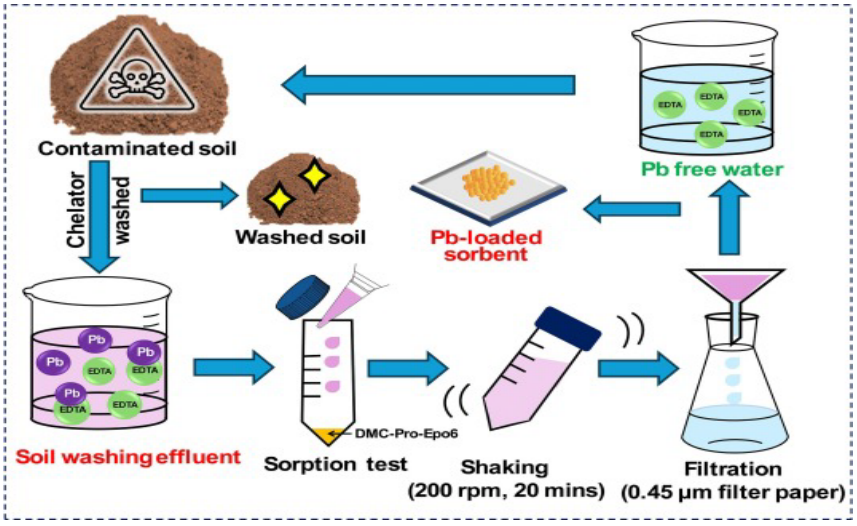

Fig. 4. Schematic illustration of the proposed Pb (II) extraction pathway from chelator-enriched soil washing effluents.

In the past, most of the research focused on individual removal of polycyclic aromatic hydrocarbons (PAHs) or heavy metals (HMs) from the water sources. The co-existence of PAHs and HMs in water is a prevalent problem; their simultaneous mitigation is highly desirable and interesting. These contaminants have different properties and compositions that make it even more difficult to remove with the use of conventional procedures. The elimination of the PAHs is reported using different adsorbents such as bentonite [33], chitosan [34], peat moss [35], activated rice husk [36], nanotubes [37], activated carbon [38], zeolite [39], biochar [40], and graphene. A group of scientists who studied these problems synthesized a crosslinked resin (CLR) with β-CD (for PAH extraction) and aspartic acid and methylenephosphonate motifs (as scavengers for Pb (II) and Hg (II)) [41].

In addition to lead, hexavalent chromium (Cr (VI)) is a toxic and carcinogenic pollutant. Ion-exchange sorbents are widely used for its selective detection. Accurate measurement of Cr (VI) in soil, water, and industrial waste is vital for environmental safety [42]. Thakur *et al.* studied this problem in detail and proposed a new sorbent. These sorbents are valued for their high selectivity and separation ability. Their performance depends on factors such as pH, temperature, and competing ions. The synthesis, modification, and characterization of ion-exchange sorbents help improve capacity and selectivity [43].

Along with complex organic sorbents, inorganic sorbents are also widely used. Zeolites are widely applied as sorbents because they are inexpensive and available in large quantities. They also show excellent chemical and thermal stability, which allows regeneration and reuse for several cycles. Another advantage is their good selectivity for exchanging different cations at room temperature. During this process, they release non-toxic exchangeable cations from their structure. Zeolites also possess a large surface area, high ion-exchange capacity, and a suitable tetrahedral pore network. These properties make them effective for heavy metal removal [44].

Natural zeolite has been successfully used to remove cadmium from aqueous solutions [45]. In addition, both natural zeolites and those impregnated with silver species have shown high efficiency in removing mercury from water (Figure 5) [46].

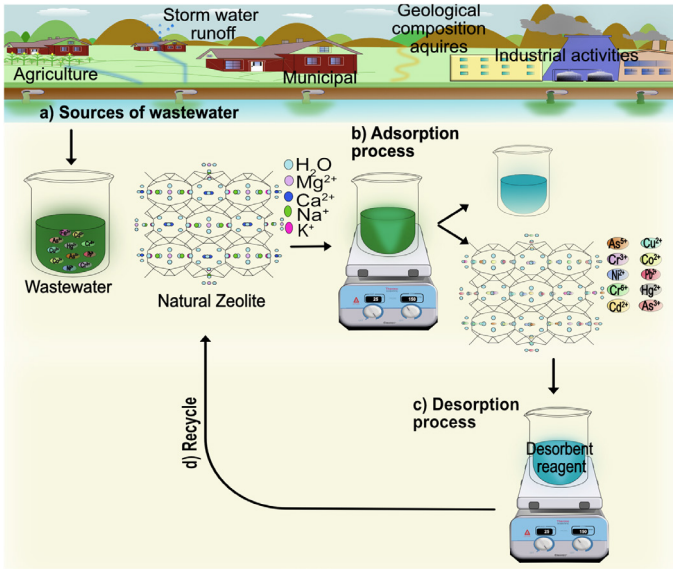

Fig. 5. An overview of the research on the removal of heavy metals with natural zeolites.

In another study one gram of natural zeolite (NZ) was mixed with 100 mL of 1 mol L-1 sodium chloride solution. The mixture was stirred at 100 rpm for 1 hour at 30 °C. Afterward, the NZ was filtered, washed with MilliQ water, and dried at 60 °C for 2 hours. This process produced Na(I)-enriched zeolite, referred to as NZ-Na. This sorbent was used to remove nickel from water. At higher temperatures, the entropy change (ΔS°) increased. This was due to the formation of more heterogeneous energetic microstates compared to 30 °C. In other words, ions such as K^+, Ca^{2+}, and Mg^{2+} played a greater role in

Ni (II) sorption at 50-70 °C than at 30 °C. Nickel ions were able to occupy a wider range of active sites with different affinity energies, created by the exchanged compensation ions on the NaCl-treated zeolite surface. As a result, the system showed greater molecular disorder and randomness at higher temperatures [47]. Finally, the eco-friendly nature of NaCl-treated zeolite adds value for future applications. The spent zeolite could be reused in agriculture as a fertilizer additive, while the recovered Ni could serve as a chemical reagent. Additionally, ammonium chloride generated in the process may also be applied as fertilizer [48].

Carbon capture and storage (CCS) technologies have recently gained significant attention as a key strategy for reducing greenhouse gas emissions. Developing cost-effective and efficient methods for capturing and storing CO_2 is essential [49].

Among different CO_2 capture technologies, solid sorbents are especially attractive due to their high adsorption capacity, low energy consumption, and ease of operation. Calcium oxide (CaO) is considered one of the most promising sorbents because it is abundant, reactive, inexpensive, and environmentally friendly. CaO captures CO_2 by forming $CaCO_3$ through a reversible reaction [50].

A group of scientists synthesized sorbents from hollow microtubules of dolomite using absorbent paper as a biological template. Mn/Fe doped dolomite was used as the raw material. These sorbents showed strong stability during CO_2 capture cycles. After 20 cycles, the sorbent prepared by the wet method lost only a small capacity (0.12-0.32 %), indicating good adaptation to the calcination temperature. Drying at 80 °C for 6 hours was found to be important for maintaining the hollow microtubule structure and improving cycle stability. The Dry-800-c sorbent showed the best CO_2 capture performance (69 %), mainly due to the complexation effect of citric acid. In conclusion, hollow microtubule dolomite-derived sorbents are promising materials for direct solar-driven CaL systems for CO_2 capture (Figure 6) [51].

Additionally, porous organic polymers with polar groups are useful for environmental applications. They can capture CO_2 and remove toxic metal ions. Two azo-linked polymers, called man-Azo-P1 and man-Azo-P2, were synthesized in water. They were made by reacting benzidine and methylenedianiline with 1,3,5-trihydroxybenzene. Man-Azo-P1 had a surface area of 290 $m^2\ g^{-1}$. Man-Azo-P2 had a surface area of 78 $m^2\ g^{-1}$. The azo (–N=N–) and hydroxyl groups gave the polymers strong adsorption ability. Man-Azo-P1 captured 32 $cm^3\ g^{-1}$ of CO_2 at 273 K and 1 bar. It also removed Pb, Cr, As, Ni, Cu, and Hg ions effectively. These results show that azo-linked POPs are stable sorbents. They can be applied in both CO_2 capture and heavy metal removal [52]. In a separate study, nanocarbon-based sorbents were synthesized for protection against a wide range of toxic chemical substances. Activation of the precursors led to the formation of numerous micropores and mesopores, thereby increasing the specific surface area and improving sorption efficiency. Walnut shell was chosen as the main raw material due to its low mineral content, high carbon content, and low levels of sulfur, nitrogen, and ash. This made it highly suitable for conversion into activated carbons used in food, medical, and environmental applications.

The preparation process included grinding, sieving, washing, and drying, followed by activation and metal impregnation. Characterization confirmed a well-developed porous texture and favorable surface chemistry. Breakthrough-time experiments demonstrated that Cu- and Co-impregnated activated carbons showed superior sorption of both organic vapors (cyclohexane, dichloroethane mixtures) and inorganic gases (SO_2, NH_3). Among them, cobalt-impregnated carbons derived from walnut shell and rice husk displayed the most promising results. These findings highlight their potential as efficient, low-cost, and eco-friendly sorbents for environmental protection and safety applications [53].

The physical adsorption of CO_2 onto biomass has not been fully studied, but this study used molecular modeling to evaluate the interactions of different biomass components with CO_2. The findings showed that adsorption occurs through a "CO_2 - water - biomass" interaction network, where water molecules act as the main mediators. CO_2 binds to water via CO-OH interactions, while water simultaneously interacts with biomass via hydrogen bonds. The moisture content was found to be an important factor controlling the adsorption efficiency. It was estimated that 1g of biomass adsorbs 5 to 56 g of CO_2 at 230-310 K and atmospheric pressure [54].

In other studies, the simultaneous adsorption of toxic gases phosphine and hydrogen sulfide has been investigated. In this study, a N-doped MWCNTs adsorbent loaded with CuO (N_XCu_Y@MWCNTs) was synthesized by one-pot method and used for the simultaneously removal of PH_3 and H_2S at low temperature and low oxygen conditions. As expected, N_XCu_Y@MWCNTs showed excellent adsorption-oxidation performance for the simultaneously removal of PH_3 and H_2S. Strikingly, the deactivated N_XCu_Y@MWCNTs also exhibited excellent activity for photocatalytic degradation and adsorption of Rhodamine B (Rh B), which significantly reduces the environmental pollution and resource waste associated with spent adsorbents. A novel and efficient adsorbent (N_XCu_Y@MWCNTs) using copper nitrate, urea, and multi-walled carbon nanotubes as raw materials was synthesized through a one-pot method (Figure 7) [55].

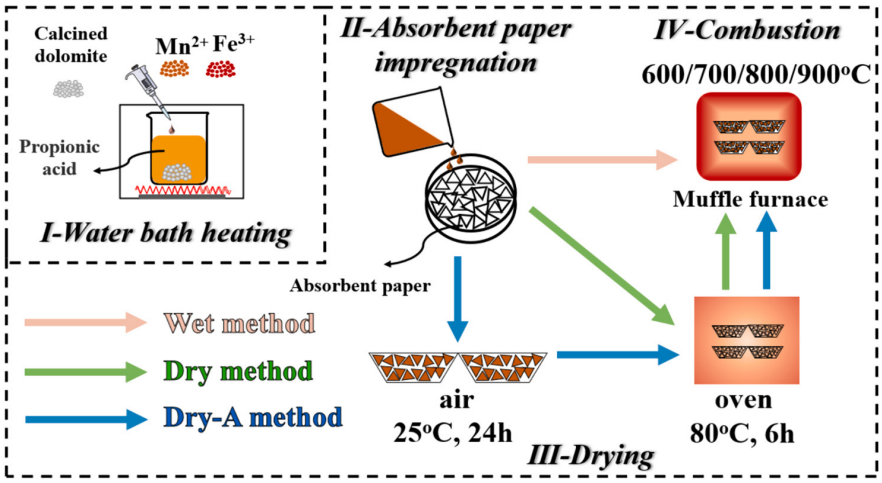

Fig. 6. Schematic diagram of the synthesis of dolomite-derived sorbents [52].

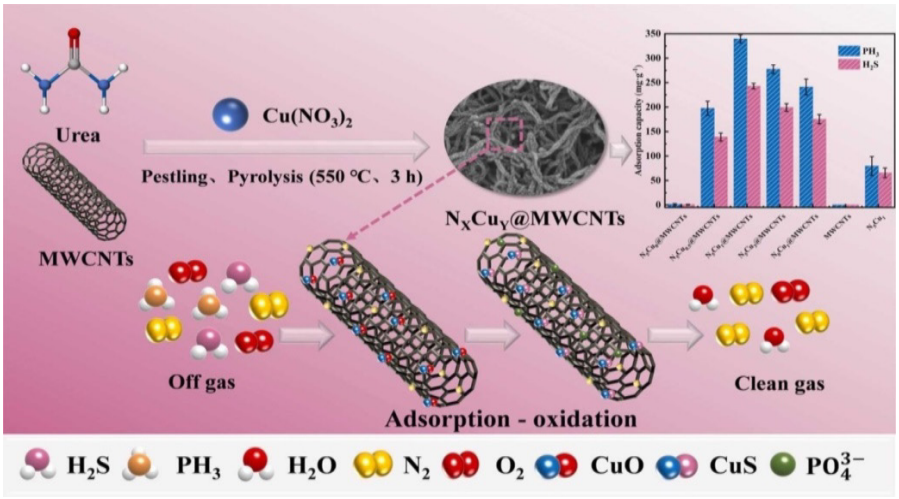

Fig. 7. Operating mechanism of the (NXCuY@MWCNTs) sorbent [55].

This adsorbent exhibit excellent performance in the simultaneous adsorption-oxidation of PH_3 and H_2S [55]. In addition, Coal gasification improves the environment and supports economic growth.

However, H_2S formed during gasification causes equipment corrosion, catalyst poisoning, and product contamination. Therefore, removing H_2S is essential for clean coal use. Recent studies explored high-temperature coal gas cleaning with metal oxide sorbents such as Zn, Mn, Fe, Cu, and Ce.

The desulfurization process is a gas-solid reaction that depends strongly on the pore structure of the sorbent. In this work, a new strategy is proposed. Highly dispersed Fe nanoparticles were anchored on carbon nanofibers (CNFs) using electrospinning and template methods under microwave heating.

A series of Fe-MCNF sorbents were first prepared by co-electrospinning polyacrylonitrile (PAN) with $Fe(acac)_3$. The method of electrospinning combined with template methods and microwave calcination was employed to synthesize the Fe NPs sorbents with different pore structures for H_2S removal [56].

4. Obtaining modified biosorbents and their importance.

Biosorbents are sorbents derived from living or dead biological sources (such as lignin, cellulose, chitin, algae, bacterial cell walls, shell wastes, etc.). Their main advantages are as follows:

Low cost and availability – they can be obtained from agricultural residues, wood, stalks, shells, and other by-products, making their production inexpensive.

Environmentally friendly – unlike synthetic polymers, they are non-toxic and biodegradable.

High selectivity – functional groups (–OH, –COOH, –NH_2, –SH) enable strong binding with heavy metal ions.

Regenerability–biosorbents can often be regenerated by washing or changing the pH.

Stability – some (such as chitosan- or lignin-based sorbents) maintain their functionality in water and across a wide pH range.

Agricultural by-products, natural substances, and bio-sorbents can serve as cost-effective alternatives for adsorption. Recent studies suggest that agricultural by-products hold promise as affordable sorbents for

removing dyes from wastewater. There are various methods available to modify the bio-adsorbent for dye adsorption which is shown in the (Figure 8) [57].

Chemical modification is considered one of the most efficient methods for enhancing the adsorption performance of sorbents. Acid and alkali treatments are the most common approaches, providing pollutant removal efficiencies of up to 95-99 %. Acid modification, typically carried out by wet oxidation, involves the use of mineral acids (e.g., HNO_3, HCl, H_2SO_4, H_3PO_4) or organic acids (e.g., oxalic, carboxylic, acetic acids). These treatments introduce surface charges and functional groups that facilitate the adsorption of positively charged metal ions and other contaminants [58]. *Physical modification* of sorbents is often performed through heat treatment, where the material is exposed to a specific temperature for a defined period followed by controlled cooling. This process reduces internal stresses, enhances dimensional stability, and improves the overall adsorption efficiency of bio-based sorbents. Owing to its simplicity and versatility, heat treatment is considered an effective approach for tailoring the structural and functional properties ofsorbents for various environmental applications [59].

Biological modification of sorbents involves the use of microorganisms, enzymatic agents, or genetic engineering techniques to enhance their surface chemistry and functionality. Such approaches improve the structural properties and adsorption capacity of bio-based sorbents, making them more effective for removing various pollutants from aqueous and gaseous media [60].

Composite Improving the effectiveness and durability of bio-adsorbents towards eliminating dyes in wastewater remediation via composite alteration is a viable method. The adsorption efficacy of bio-adsorbents may be augmented by including composites, including tetraethylenepentamine (TEPA), into amino terephthalic acid-modified AC. Research indicates that composite alteration significantly enhances uptake capacity in comparison to unmodified bio-adsorbents, underscoring the efficacy of this adaptation technique in improving dye removal efficiency [61]. *Graft polymer*. A valuable method for enhancing the uptake capacity of bio-adsorbents for eliminating colors in wastewater purification is graft polymer alteration. The uptake capacity and selection of bio-adsorbents, like polyacrylic acid, may be significantly improved by graft polymerization onto their surface [62].

Many experiments have been conducted to obtain modified natural sorbents, including used poultry feathers (PFs) as a biosorbent to remove six heavy metals (Cr^{6+}, As^{3+}, V^{5+}, Co^{2+}, Ni^{2+}, Cd^{2+}) from contaminated water. The spent biosorbent was also evaluated for its thermal and energy potential. PFs were modified with tetrahydrofuran (THF), and the process was optimized using response surface methodology (RSM). The best pre-treatment conditions were 30 °C, 47 min, and 0.015 g ml^{-1}, while optimal biosorption was achieved with 0.17 g PF and 0.5 h contact time. Under these conditions, removal of Co^{2+}, Ni^{2+}, Cd^{2+}, and V^{5+} increased, whereas Cr^{6+} and As^{3+} removal slightly decreased [63].

Developing green materials for heavy metal removal is both environmentally and economically important. In this work, lettuce leaves (LC), a low-cost agricultural waste, were modified with alginate (ALG) and diethylenetriaminepentaacetic acid (DTPA). The modified LC/ALG-DTPA biosorbent was designed for the adsorption of Pb^{2+} ions. Lettuce leaves harvested in December DTPA, sodium alginate, ammonium solution, and other chemicals were supplied by Merck. All experiments were carried out with double-distilled water, and the pH was adjusted using NaOH or HCl. The two-step modification with ALG and DTPA improved Pb^{2+} adsorption efficiency. This synergistic effect makes LC/ALG-DTPA a promising and sustainable material for the treatment of lead-contaminated water (Figure 9) [64].

In a subsequent study, Lettuce leaves (LC) were selected as a cheap and green biosorbent. They were modified in two steps with sodium hydroxide (NaOH) and ethylenediaminetetraacetic acid (EDTA). NaOH removes waxes, fats, and lignin from the surface. This exposes functional groups like –OH, $–NH_2$, and –COOH. It also improves cellulose strength and ion exchange ability. EDTA forms stable complexes with heavy metals such as Pb^{2+}, Ca^{2+}, and Mg^{2+}. It is widely used because of its strong complexation ability. The combined modification (LCNE) increased Pb^{2+} removal efficiency. This was achieved by cleaning the surface with NaOH and adding EDTA as a coordinating agent (Figure 10) [65].

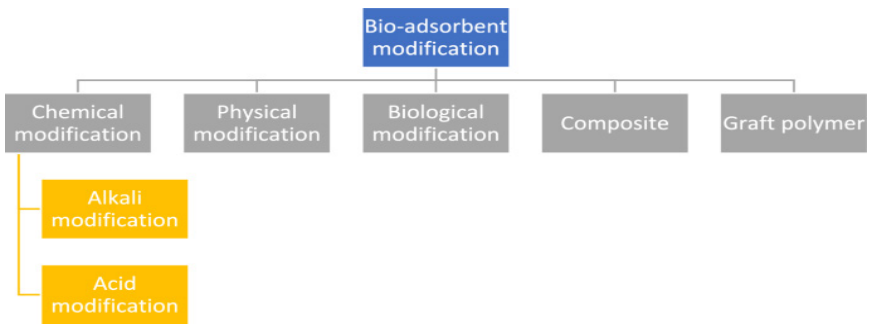

Fig. 8. Modification of bio-adsorbent.

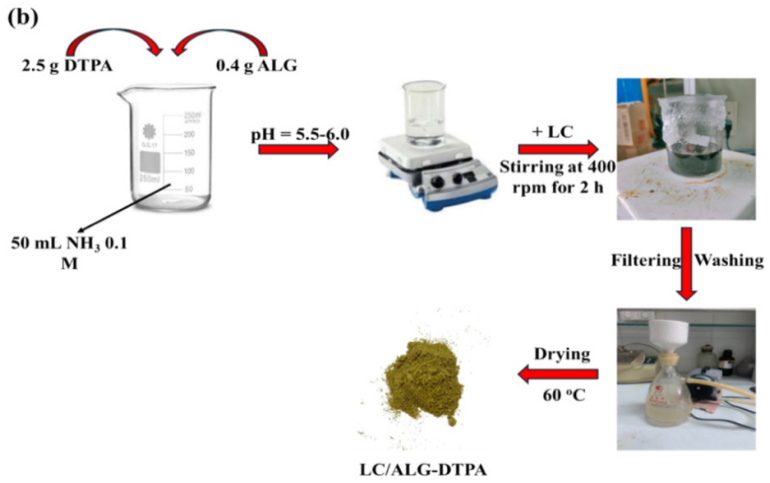

Fig. 9. Preparation process of (a) LC and (b) LC/ALG-DTPA biosorbent.

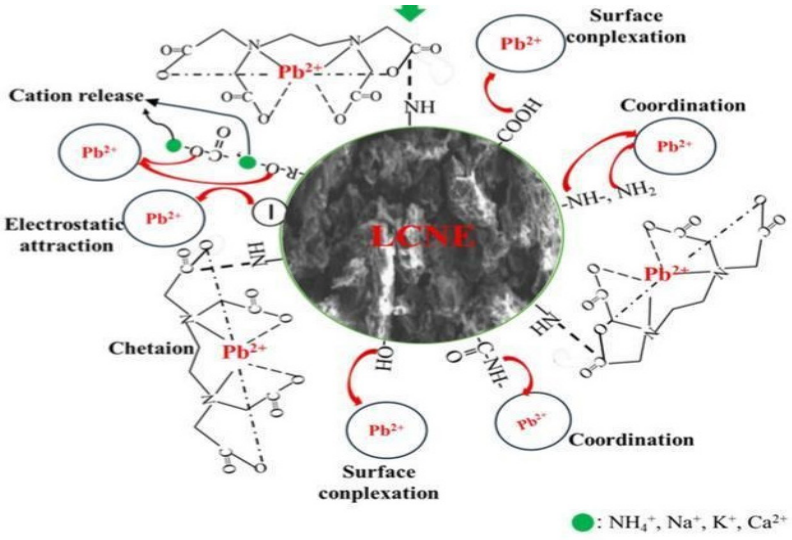

Fig. 10. Pb uptake by modified biosorbent.

In a subsequent study, Lettuce leaves (LC) were selected as a cheap and green biosorbent. They were modified in two steps with sodium hydroxide (NaOH) and ethylenediaminetetraacetic acid (EDTA). NaOH removes waxes, fats, and lignin from the surface. This exposes functional groups like –OH, –NH_2, and –COOH. It also improves cellulose strength and ion exchange ability. EDTA forms stable complexes with heavy metals such as Pb^{2+}, Ca^{2+}, and Mg^{2+}. It is widely used because of its strong complexation ability. The combined modification (LCNE) increased Pb^{2+} removal efficiency. This was achieved by cleaning the surface with NaOH and adding EDTA as a coordinating agent (Figure 10) [65]. In related work, M Plaza-González, M Bueno-Abarca a new biosorbent was obtained by modifying the luffa plant. Luffa (Luffa acutangula or Luffa aegyptiaca) is a natural fiber from the Cucurbitaceae family. It contains cellulose (55-90 %), hemicellulose (8-22 %), and lignin (10-23 %). The composition depends on species, soil, irrigation, and temperature Luffa has a large surface area. It is cheap and biodegradable. Because of these properties, it is used as a sorbent in analytical extractions. Industrially, luffa is applied for heavy metal removal, dye decolorization, and ethanol production. It is naturally hydrophilic, but pretreatments can change its surface polarity. For example, functionalization with stearic acid allows oil separation from water. Luffa-based sorbents are eco-friendly and low-cost. Functionalization with stearic acid improved their efficiency for detecting PAHs in water. Enrichment factors were 11-30, and recoveries ranged from 72-88 % [66].

Another interesting work in obtaining sorbents from waste is investigated the removal of Congo red dye from industrial wastewater. The researchers used low-cost nano-biosorbents prepared from agricultural wastes such as magnetic orange peel, peanut shells, and tea waste. Tea waste showed the highest removal efficiency of 94 %. This was due to its high porosity and the presence of active functional groups. Peanut shells removed 83 % of the dye, while orange peel achieved 68 %. These findings demonstrate that agricultural waste-based nano-biosorbents are practical for dye removal. They also offer a sustainable method for wastewater treatment and environmental protection [67].

5. Obtaining polymer composite modified sorbents.

Polymer sorbents are specially synthesized or modified polymer-based materials designed for the removal of various pollutants. They can be prepared from natural polymers (such as chitosan, cellulose, lignin) or synthetic polymers (such as polystyrene, polyaniline, polyacrylic acid, polyamide) [68]. The main advantages of polymer sorbents are as follows:

High selectivity – The incorporation of specific functional groups (–NH_2, –COOH, –OH, –SO_3H, etc.) into the polymer backbone allows selective interaction with target metal ions or organic molecules.

Structural flexibility – Polymers can be fabricated in various forms (granules, films, fibers, nanocomposites), which broadens their application fields.

Strong mechanical stability – Compared to many natural sorbents, polymer sorbents are more resistant to deformation.

Chemical resistance – They can remain stable in acidic, alkaline, or organic solvent environments.

Reusability – Many polymer sorbents can be regenerated and used multiple times without significant loss of efficiency.

High surface area and adsorption capacity – Particularly in nanostructured and hybrid polymer sorbents, this property is significantly enhanced.

Low-cost and accessible raw materials – Some polymer sorbents can even be synthesized from agricultural wastes or recycled plastics.

Polymeric adsorbents are valued for their mechanical strength, stability, and tunable surface properties. Chemical modification allows the introduction of functional groups, improving adsorption capacity and selectivity toward specific contaminants. Their hierarchical pore structures further enhance efficiency. Unlike conventional materials such as activated carbon, many polymeric adsorbents are regenerable and reusable. Moreover, bio-based polymers like chitosan and cellulose add sustainability through biodegradability and eco-friendly sourcing [69].

Polymeric materials are increasingly recognized as effective adsorbents for water purification. Their adjustable surface chemistry, strong mechanical stability, and versatile structures allow them to be tailored for specific adsorption purposes. By introducing or modifying hydrophilic functional groups, these materials can achieve improved selectivity and stronger interactions with targeted pollutants [70].

Recent studies emphasize the importance of advanced materials in addressing environmental pollution. Innovative polymers have shown strong potential in this field due to their structural advantages. Their large surface area offers numerous active sites for adsorption, while porous frameworks enable fast diffusion and accessibility. In addition, polymers maintain high mechanical strength and chemical stability, making them suitable for demanding water treatment conditions without notable degradation [71].

A wide range of polymeric adsorbents has been explored for water treatment applications. Polyaniline (PANI) exhibits excellent efficiency in capturing heavy metals and organic pollutants, while chitosan, obtained from chitin, provides abundant functional groups for contaminant binding. Polyacrylamide (PAM) and its derivatives, widely used as flocculants, also act as efficient adsorbents for dyes and metal ions. Similarly, hydrogels based on polyvinyl alcohol (PVA) show strong potential for removing organic compounds due to their high swelling capacity and water retention [72].

The authors observed that introducing functional groups during modification improved the adsorption capacity for metal ions. At the same time, the material showed strong antibacterial activity against both Gram-positive and Gram-negative bacteria. This dual function makes thiosemicarbazide-modified chitosan a promising candidate for pollutant removal and pathogen control in water treatment. Kumar et al. reported these findings [73].

Polyaniline (PANI)-based adsorbents have gained much attention because of their conductive nature. This property makes them useful in both environmental remediation and antibacterial applications. Composite adsorbents such as PANI–Ti (IV) and PANI–ZrO_2 show high efficiency in pollutant removal. They are also effective in controlling bacterial growth. Studies by Bushra et al. confirmed their improved performance compared with pure PANI [74].

Central Asian scientists have also conducted a number of scientific research studies on the production of modified polymer sorbents. one of them is as follows This study focuses on synthesizing and evaluating a chelating sorbent for extracting non-ferrous and noble metal ions. A sulfur-containing sorbent was prepared using carbamide, formaldehyde, and dithizone. The effects of molar ratios of starting materials on the structure and physicochemical properties were investigated. The optimal synthesis conditions were found at 90 °C with a reaction time of 2.5-3 hours, yielding an exchange capacity of 3.8 mg-eq/g in 0.1 N HCl solution. The best performance was achieved with a 1:2:0.5 molar ratio of carbamide, formaldehyde, and dithizone. IR spectroscopy supported the proposed reaction pathway for sorbent formation. The static exchange capacity values (mg-eq/g) for metal ions were: Cu (II) – 2.75, Zn (II) – 2.83, Ni (II) – 2.72, and Ag (I) – 3.12 [75].

In another article presents a study of a complexing ion exchanger synthesized from urea, formaldehyde, and phenolsulfophthaleic acid. The influence of temperature and molar ratios of the starting materials on its properties was evaluated. A structural model of the synthesized ion exchanger is proposed. The exchange properties with Cu (II), Zn (II), and Ni (II) ions were determined. In addition,

the IR spectra and thermal characteristics of the obtained ion exchanger were analyzed. The IR spectroscopic and thermal properties of a sorbent based on urea, formaldehyde, and diphenylthiocarbazone, which have complex-forming properties with d-metal cations, were also studied [76].

This study reports the synthesis of a sulfur-containing polymer sorbent incorporating diethyldithiocarbamate (DEDTC) as a functional monomer. Poly(diethyldithiocarbamate) materials were prepared through radical suspension polymerization. The synthesis conditions were optimized, and the structural parameters and properties of the polymers were characterized. Their sorption performance was evaluated using modern physicochemical methods and applied to extract Cu (I), Ni (II), and Zn (II) ions from wastewater of the Termez Reservoir [77]. A polymer based on urea, formaldehyde, and phenylsulfophthaleic acid (MPF) was synthesized. The reaction was carried out in a three-neck flask with a condenser and stirrer. First, 12 g of urea (0.2 mol) was dissolved in 40 ml of formalin (0.5 mol) at 40 °C. Then, 50 ml of an aqueous solution of phenylsulfophthaleic acid (7 g, 0.02 mol) was added dropwise. The mixture was heated to 95-100 °C and stirred for 2 hours. As a result, a yellow-orange resin was obtained (Figure 11).

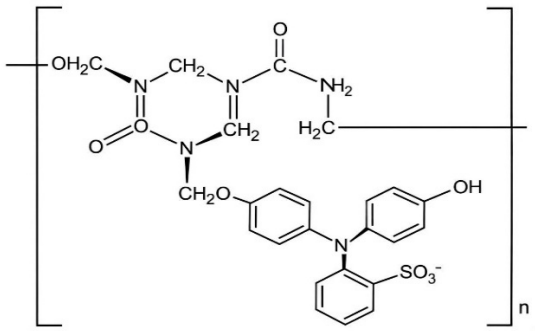

Fig. 11. The proposed structure of CFP polyampholyte.

The product was dried at 80-85 °C for 24 hours, ground, and washed with 5 % NaOH, followed by distilled water. The final material consisted of fine red granules. It was insoluble in water but soluble in ethanol. The reaction yield was about 90 %. The optimal ratio of urea, formaldehyde, and acid was 2:5:0.2. This composition gave the best ion-exchange and adsorption properties [78]. In this study, a urea-formaldehyde resin was modified with 2,4-diphenylhydrazine to synthesize a new sorbent. The chemical composition and physicochemical properties of the obtained material were investigated, and its ion-exchange behavior was evaluated. Experimental results demonstrated that the sorbent possesses high efficiency in removing heavy metal ions. Moreover, the modification process enhanced both the selectivity and stability of the sorbent. These findings confirm the potential application of the synthesized sorbent in environmental protection and industrial wastewater treatment [79].

A group of scientists, during their scientific research, proposed a new polymer sorbent: Polymeric adsorbents with sulfur and amide groups are effective for selective mercury removal. Thiol, thioether, and polymer-supported ligands such as xanthate, thiourea, and dithizone have shown strong affinity to mercury ions [80]. Recently, sulfonamide-based adsorbents gained attention due to their stability in acidic and basic media. A new material, PS-TUR, was synthesized by chlorosulfonation, sulfonamidation, and urethane modification. Its structure and surface properties were analyzed using FTIR, SEM-EDX, XPS, BET, and surface charge measurements. Inverse gas chromatography (IGC) was applied to study adsorbent–adsorbate interactions. Functional groups like urethane, urea, and amide enhance covalent binding of mercury from water, making PS-TUR a promising adsorbent for mercury remediation [81].

In the following study, A new adsorbent was developed by modifying polystyrene (PS) with ethanolamine and adding chromium hydroxide nanoparticles (Cr@EA-PS). The material showed good efficiency for removing cadmium (Cd (II)) ions from water. Dual modification improved the surface properties and functional groups compared to unmodified PS. Characterization, kinetic, and isotherm studies confirmed the adsorption mechanism. The study also showed that Cr@EA-PS is cost-effective and suitable for wastewater treatment [82]. Bivalves, such as the blood cockle (*Tegillarca granosa*), accumulate heavy metals in their tissues due to their filter-feeding behavior. Consumption of these contaminated bivalves can expose humans to heavy metal toxicity. This study evaluated the adsorption method for removing lead (Pb), cadmium (Cd), and arsenic (As) from *T. granosa*. Results showed that the initial concentrations of Pb and As exceeded WHO limits. To reduce heavy metal content, lemon and mango peels were applied as natural waste-based adsorbents. FTIR spectra confirmed the presence of hydroxyl and carboxylic groups in the peels, which contributed to effective adsorption. Experiments were conducted under varying dosages, contact times, and reaction temperatures. Using lemon peels, the maximum removal efficiencies reached 59.65 % for Pb, 88.89 % for Cd, and 67.54 % for As. With mango peels, the removal rates were higher, achieving 70.18 % for Pb, 100 % for Cd, and 84.71 % for As. Overall, the results demonstrate that both lemon and mango peels can serve as efficient natural adsorbents for heavy metal removal from *T. granosa* [83-86]. A Ni-polyacrylamide composite was synthesized for wastewater treatment. First, polyacrylamide particles were prepared by high internal phase emulsion (HIPE) polymerization. Then, these particles were coated with nickel hydroxide nanoparticles to obtain the adsorbent. The composite was tested for the removal of methylene blue dye. Adsorption performance was studied under

different conditions such as pH, contact time, initial concentration, and adsorbent dose. The maximum adsorption capacity was 14.3 mg g^{-1}. This was attributed to the presence of both organic and inorganic functional groups in the structure. Kinetic studies showed a pseudo-second-order model. The equilibrium data fitted the Langmuir isotherm. Thermodynamic analysis confirmed that the process was feasible, spontaneous, endothermic, and mainly driven by physisorption [87]. In this article, the sorption properties of a new polyampholyte were studied for the first time.

The polymer was synthesized by covalent fixation of ortho-aminobenzoic acid onto an "epoxymol" epoxy resin and polyethylene polyamine matrix. The polyampholyte was tested for complexation with copper, nickel, zinc, cobalt, and silver ions. The structures of the polymer and its metal complexes were characterized using IR-spectroscopy. Elemental analysis confirmed the formulas of the obtained coordination compounds. Thermal studies showed that the sorbent is stable up to 200 °C. The material is recommended for practical application in removing d-metal ions from solutions. The sorption dependence on pH was also investigated. Results indicated that sorption is more efficient in slightly acidic media [88, 89].

Precious metals (PMs) including Au, Pt, Pd, Ru, Rh, Ir, and Ag possess exceptional physicochemical characteristics that give them high economic importance. Their remarkable corrosion resistance, elevated melting points, strong catalytic activity, adjustable electrical and thermal conductivity, and effective coordination behavior make them highly attractive materials [90]. Due to these unique properties, PMs are widely employed in chemical and petroleum processing as catalysts, in the automotive sector, electronic and electrical devices, jewelry production, and pharmaceutical synthesis [91, 92].

Precious metals (PMs) released from mining and industrial activities often accumulate as waste, causing both environmental concerns and economic losses due to insufficient recycling [93]. For instance, discarded PMs from electronic devices were valued at nearly $ 62.5 billion in 2020 [94]. This has driven researchers to develop greener and more cost-effective recovery methods [95]. Polymers, especially as sorbent materials, are drawing attention of researchers because of the ease of synthesis, ecofriendly properties, dispersibility and the possibility of integrating functional groups in the polymer film for efficient extraction of metals [96]. Polymerization of pyrrole-1-carbodithioic acid on silica coated Fe_3O_4 nanoparticles created the magnetic sorbent, PPy-CS_2@SiO_2@Fe_3O_4, for extraction and analysis of precious metals.

To solve the above problems Abiral Poudel and others Polymerization of pyrrole-1-carbodithioic acid on silica coated Fe_3O_4 nanoparticles created the magnetic sorbent, PPy-CS_2@SiO_2@Fe_3O_4, for extraction and analysis of precious metals. PPy-CS_2@SiO_2@Fe_3O_4 is an air-stable, water-dispersible granular composite effectively applied for magnetic solid-phase extraction of precious metal ions such as Ru, Rh, Ir, Pd, Pt, and Au. Optimal performance was observed at pH 6 with 15 mg of sorbent and a 15 min extraction time. The material exhibits high sorption capacities for Pd^{2+} (163.0 mg g^{-1}) and Au^{3+} (132.7 mg g^{-1}), indicating its potential for larger-scale applications. Moreover, its efficiency remains unaffected by the presence of excess co-existing metal ions, making it suitable for complex mixtures (Figure12) [97].

In another study, focused on recovering naproxen from aqueous solutions using solid polymer sorbents (Sepabeads® SP850, Amberlite® XAD-4, and Diaion® HP-20) impregnated with a novel ionic liquid, 1-propyl-3-undecanoylpyridinium bromide. The incorporation of this ionic liquid into polymer matrices was evaluated for its potential in naproxen recovery. Solvent-impregnated resins were prepared using both wet and dry impregnation methods. Experimental results demonstrated the effectiveness of the synthesized resins in naproxen removal, achieving efficient extraction within 5-10 minutes [98].

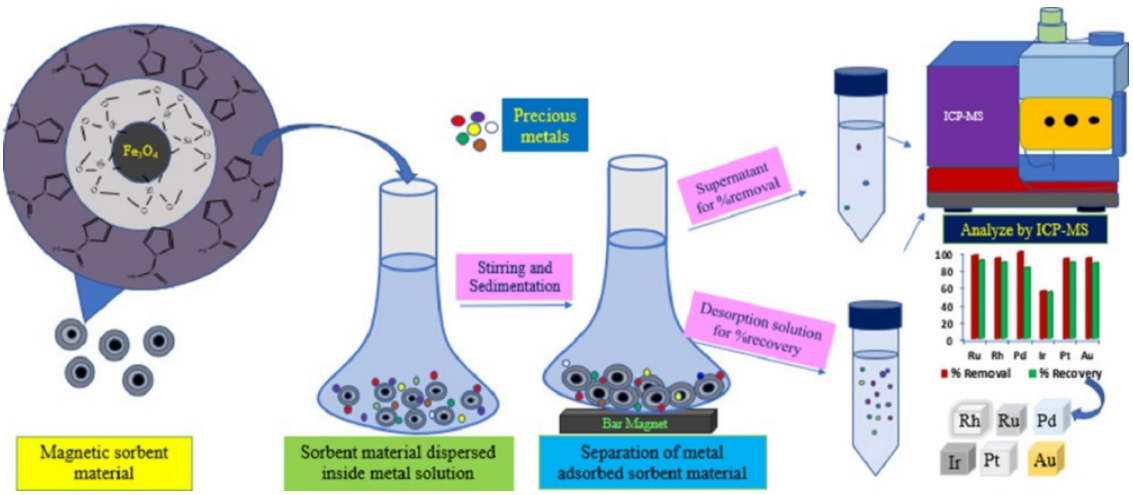

Fig. 12. Schematic representation of the synthesis of PPy-CS_2@SiO_2@Fe_3O_4.

Recent advances in sorbent sample preparation have led to the development of advanced strategies that allow the efficient handling of complex matrices in qualitative and quantitative analyses. These methods typically involve sample cleanup and preconcentration of the target analytes prior to instrumental analysis. One of the most important factors in this process is the sorbent material, as it governs the interaction between the analytes and the extraction phase. Therefore, choosing the appropriate sorbent is crucial for efficient and selective extraction. In recent years, a variety of sorbent materials have been developed with high surface area, high porosity, and tunable selectivity [99-100].

Sorbent materials are now central to both conventional and miniaturized solid-phase extraction techniques. They are generally classified into synthetic and natural-based sorbents, each possessing distinctive physicochemical properties that enable their application across a range of analytical protocols. Synthetic sorbents, including metal-organic frameworks (MOFs), restricted access media (RAM), molecularly imprinted polymers (MIPs), cryogels, and carbon-based materials, have shown exceptional adaptability for diverse applications. Despite their advantages, these materials are often synthesized via solvent-intensive methods that pose environmental and health concerns.

Consequently, growing interest has shifted toward green sorbents**,** derived from biopolymers, activated carbon, biochar, and other natural sources. These sustainable alternatives offer low-cost production and favorable sorption properties but also face challenges such as non-standardized synthesis procedures and limited selectivity, often requiring further modification to enhance their affinity for target analytes. Addressing these limitations remains essential for their broader implementation in analytical sample preparation [101-124]

6. Conclusion

It has been demonstrated that the modification of sorbents with functional groups, nanostructures, or hybrid composites significantly improves their adsorption capacity, selectivity, and reusability. The synergistic effect between the polymer matrix and incorporated modifiers not only governs the efficiency of target ion removal but also influences stability, regeneration performance, and environmental safety.

Despite the promising results obtained at the laboratory scale, challenges remain in scaling these advanced sorbents for industrial applications. These challenges include high synthesis costs, complex modification procedures, difficulties in achieving homogeneous distribution of active sites, and a lack of long-term performance data under real wastewater conditions.

To overcome these limitations and guide future development in the field of sorbent design, the following research directions are proposed:

*Smart and Responsive Sorbents***:** The incorporation of stimuli-responsive groups (e.g., pH, redox, or light-sensitive moieties) can enable controlled adsorption and desorption processes, allowing more efficient regeneration and reuse.

Self-Regenerating Sorbent Systems: Embedding functional micro- or nanocapsules capable of releasing regenerating agents during sorption cycles could reduce operational costs and prolong sorbent lifetime.

*Green and Sustainable Sorbents***:** Future work should focus on biodegradable polymers (e.g., cellulose, chitosan, lignin-based materials) and environmentally benign modifiers that ensure both high adsorption efficiency and compliance with environmental regulations.

*Performance Optimization for Real Systems***:** Comprehensive studies under diverse conditions (acidic, alkaline, saline, and multicomponent wastewater systems) are necessary. Advanced characterization techniques, such as FTIR, SEM-EDX, XPS, and adsorption isotherm/kinetic modeling, should be integrated to understand sorption mechanisms in real environments.

By addressing these directions, the development of next-generation modified sorbents can lead to materials that are highly efficient, selective, scalable, and environmentally sustainable. Such advances will play a crucial role in solving global challenges related to heavy metal pollution and wastewater treatment.

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