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MODERN ANALYTICAL APPROACHES TO THE DETERMINATION AND REMOVAL OF HEAVY METAL IONS FROM AQUEOUS MEDIA

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Introduction. The intensive development of industry, urbanization, and the growth of technogenic load have led to a significant increase in the concentration of heavy metal ions in natural and wastewater. These pollutants are characterized by high chemical resistance, the ability to accumulate bio, and a pronounced toxic effect on biological systems, which determines their particular ecological and sanitary hazard [1,2]. Unlike organic compounds, heavy metals do not undergo biodegradation and can circulate in the environment for a long time, transitioning from one ecosystem to another.

In this regard, analytical control methods that ensure high sensitivity, selectivity, and reliability of metal detection, as well as technologies for their effective removal from water bodies, are of particular relevance. Classical analysis methods, such as atomic absorption spectrometry and inductively coupled plasma mass spectrometry, have high accuracy but require expensive equipment and complex sample preparation [3]. This stimulates the development of alternative analytical approaches based on spectrophotometry, fluorimetry, sorption, and electrochemical methods.

In recent years, special attention has been paid to the development of integrated and hybrid analytical and technological solutions that combine selective determination, preliminary concentration, and simultaneous reduction of water environment toxicity. In this context, the role of new reagents, functional sorbents, biomaterials, and nanostructured systems is increasing [4-6].

The purpose of this review article is to systematize and critically analyze modern spectrophotometric, fluorimetric, sorption, and combined methods for determining and removing heavy metal ions from aqueous media, as well as to identify key trends and prospects for their further development in the context of analytical chemistry and environmental monitoring.

Analysis and discussion of research results. Spectrophotometric methods and complex formation. Spectrophotometry remains one of the most in-demand analytical control methods due to its simple apparatus design, high reproducibility, and the ability to selectively determine metals based on complex formation. The use of organic chromogenic reagents, including porphyrins, rhodamine dyes, and Schiff bases, allows for the formation of intensely colored complexes with metal ions, accompanied by significant changes in optical density [7,8].

An interesting area is the application of biomimetic systems based on the metallotionine detoxification mechanism. The replacement of Zn (II) ions in metallotion with more toxic metals is accompanied by the release of labile zinc, which is further recorded using highly sensitive porphyrin reagents. Such approaches demonstrate good correlation with biotests and allow for the assessment of the integral toxicity of water samples [9].

Fluorimetric methods. Fluorimetric methods are characterized by low detection limits and high selectivity, making them particularly attractive for express analysis. The formation of fluorescent complexes of heavy metals with thiol and nitrogen-containing ligands ensures effective recognition of Hg (II), Cd (II), Pb (II), and Ag (I) even in complex wastewater

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matrices [10]. Such methods are suitable for preliminary screening and rapid assessment of the degree of contamination.

Solubility Thermodynamics and Metal Precipitation. Studying the solubility and complexation balances plays a key role in developing reagent methods for water purification. It has been established that the solubility products of xanthogenates and other sulfur-containing heavy metal compounds significantly depend on the structure of the organic ligand and the environmental parameters [11]. The obtained thermodynamic data allows for the optimization of selective sedimentation processes and minimizes secondary contamination of treated water.

Nanomaterials and modern touch platforms. The rapid development of nanotechnology has led to the creation of new sensory platforms for determining heavy metals. Two-dimensional nanomaterials such as graphene, MXene, and transition metal chalcogenides provide a high active surface, improved electronic properties, and accelerated kinetics of electrochemical processes [12]. This allows for achieving ultra-low detection limits when analyzing real water samples.

Unlike highly specialized sensors, modern research is focused on creating universal platforms capable of simultaneously identifying multiple analytics and operating in a wide range of conditions.

Sorption and hybrid purification technologies. Sorption methods based on modified biomaterials are considered sustainable and cost-effective solutions. Biocarbones obtained from plant waste and functioned with acids or surfactants exhibit high sorption capacity for heavy metal ions and organic pollutants [13].

Combined technologies combining oxidation, precipitation, and sorption allow for the effective removal of both free and chelated forms of metals. The use of strong oxidizing agents such as ferrate (VI) in combination with sulfur-containing precipitators leads to a significant decrease in metal concentrations and the overall ecotoxicity of wastewater [14].

Specialization and selective separation of metal forms. The specialization of metals is of particular importance due to the differences in the toxicity of individual forms. Biosorbents, including immobilized natural materials, allow for the selective separation of, for example, Cr (III) and Cr (VI) with subsequent highly sensitive determination using atomic spectroscopy methods [15]. Such approaches combine analytical accuracy and environmental focus.

Conclusion. The conducted analysis of literature data shows that modern methods for determining and removing heavy metal ions are developing in the direction of integrating analytical and technological solutions. The most promising approaches are those based on the combination of spectrophotometric and fluorimetric methods with sorption materials and nanostructured sensors. For the practical tasks of environmental monitoring, methods that ensure not only high sensitivity and selectivity but also the possibility of assessing the integral toxicity of aquatic environments are of particular importance. Further research in the field of functional materials, hybrid technologies, and biomimetic analytical systems will contribute to the creation of effective and sustainable solutions that meet modern requirements for analytical chemistry and environmental safety.

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