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Investigating the Negative Impacts of Medical Waste on Aquatic Ecosystems – An Increasing Hazard to Water Resources and Public Health

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ABSTRACT. This paper analyzes the literature data on methods for medical waste disposal and assessment of their impact on water bodies within the context of the existing legal and regulatory framework. The relevance of the topic is due to the increasing volumes of such waste and its potential danger to the population and ecosystems. The aim of the work is to systematize and evaluate approaches to disposal and methods for analyzing water body pollution. The work was carried out as part of the research topic of the Department of Industrial Ecology, aimed at developing theoretical approaches to justifying sanitary standards for the content of medicines and their metabolites in drinking water. Determining the degree of hazard of medical waste, which is the result of this study, is necessary for the development of sound and effective strategies to reduce their negative impact on the environment and human health. The acquired understanding of the problem serves as a solid foundation for further research aimed at improving methods for managing and disposing of medical waste.

KEYWORDS: Medical waste; waste management of production and consumption; negative environmental impact; pharmaceuticals; drinking water; water body pollution

A key characteristic of environmental safety is the negative impact on the environment (NIE) stemming from both medical waste itself and the harmful (polluting) substances generated during its disposal [1]. Medical waste from healthcare organizations comprises chemical substances of varying degrees of toxicity. For this reason, disposal and neutralization of medical waste should be carried out by specialized companies that are licensed to perform this type of activity. Incineration of medical waste leads to serious pollution of the atmosphere, hydrosphere, and soil with toxic substances, and consequently, to serious health problems and diseases among the population. Improper handling of medical waste leads to a number of severe negative consequences, including: contamination of aquatic ecosystems (with antibiotics, hormonal drugs, disinfectants); soil contamination (with heavy metals, cytostatics); the spread of antimicrobial resistance; and the emergence of health risks for the population, including carcinogenesis and endocrine disruption [2].

The present study aims to address a pressing issue related to the environmental risks stemming from the handling of medical waste. In this regard, the objective of this work is to comprehensively examine existing medical waste management systems from the perspective of minimizing their negative impact on the environment.

Problem and its Connection to the Sustainable Development Goals (UN). The problem under consideration directly impacts the achievement of several Sustainable Development Goals (SDGs) formulated by the United Nations, where each of these goals is interconnected and requires a comprehensive approach to achieve sustainable development. Below is a brief description of how this problem affects each of the specified SDGs:

SDG 3: Good Health and Well-being. The problem impacts the achievement of this goal through infection prevention. Insufficient attention to this problem can lead to increased morbidity, the spread of infectious diseases, and a decline in the overall health of the population. Specifically, the uncontrolled use of antibiotics (which is part of the problem) leads to the development of antibiotic resistance, making the treatment of infections more complex and costly, and in some cases, impossible.

SDG 6: Clean Water and Sanitation. The problem is linked to achieving this goal through the prevention of pharmaceutical pollution. Contamination of water resources with pharmaceuticals poses a serious threat to human health and ecosystems. For example, the entry of pharmaceutical residues into drinking water can lead to hormonal disruptions, the development of antibiotic resistance, and other negative consequences for human health.

SDG 12: Responsible Consumption and Production. The problem impacts the achievement of this goal through the need to implement a circular economy. The irrational use of resources, waste generation, and the absence of recycling systems create a significant burden on the environment and hinder sustainable development. For example, ineffective management of pharmaceutical industry waste (expired medications, improper disposal) leads to soil and water contamination, as well as the loss of valuable resources.

SDG 14: Life Below Water. The problem is linked to achieving this goal through minimizing the entry of waste into the oceans. Pollution of the marine environment with waste, including pharmaceuticals and plastics, poses a threat to marine ecosystems and biodiversity. For example, the entry of microplastics and chemical substances into the oceans harms marine animals, contaminates food chains, and can negatively impact human health [3].

Addressing the problem under consideration requires a comprehensive and multifaceted approach that takes into account the interrelationship between human health, the state of the environment, and the principles of sustainable development.

GENERAL CHARACTERISTICS OF MEDICAL WASTE AS A SOURCE OF WATER BODY POLLUTION

In the Russian Federation, medical waste has been excluded from the scope of legislation on industrial and consumer waste due to the need to organize a special handling regime for it.

The classification of medical waste is reflected in Article 49 of Federal Law No. 323-FZ of November 21, 2011, "On the Basic Principles of Public Health Protection in the Russian Federation". The rules for handling medical waste are regulated in SanPiN 2.1.3684-21 "Sanitary and Epidemiological Requirements for the Maintenance of Territories of Urban and Rural Settlements, for Water Bodies, Drinking Water and Drinking Water Supply, Ambient Air, Soils, Residential Premises, Operation of Industrial and Public Premises, Organization and Implementation of Sanitary and Anti-Epidemic (Preventive) Measures".

However, in August of last year, Federal Law No. 306-FZ of August 8, 2024, "On Amendments to Certain Legislative Acts of the Russian Federation" was issued.

This law amends three federal laws: Federal Law No. 89-FZ of June 24, 1998, "On Industrial and Consumer Waste" (as amended on August 8, 2024); Federal Law No. 52-FZ of March 30, 1999, "On the Sanitary and Epidemiological Welfare of the Population" (as amended on August 8, 2024); and Federal Law No. 323-FZ of November 21, 2011, "On the Basic Principles of Public Health Protection in the Russian Federation" (as amended on August 8, 2024).

The amendments come into force on July 1, 2025, and now Class "A" waste is equated to municipal solid waste, and the regional operator will dispose of such waste. A number of clarifications have also been made to the procedure for disinfecting Class B, C, and D waste, which comes into force on September 1, 2026.

The following criteria for assessing water quality are presented in state standards – normalization [4]. The normalization of water quality indicators is an assessment of its suitability for various types of use by establishing quantitative criteria. There are three main types of normalization: sanitary-hygienic, ecological, and scientific-technical.

Sanitary-hygienic standards, as a rule, do not reflect the combined effects (simultaneous or sequential influence of several substances, with the same route of entry) and do not take into account the effects of complex action (entry of harmful substances into the body through various routes), as well as the combined effect of the entire variety of environmental factors. Despite these limitations, most legal acts assess water quality based on sanitary-hygienic normalization. Examples of such documents are GOST R58556-2019 "Assessment of Water Quality of Water Bodies from an

Ecological Perspective" and GOST R71327-2024" Water Quality.

Methods for determining sanitary-microbiological and sanitary-parasitological indicators in the assessment of surface water bodies and wastewater." In SanPiN1.2.3685-21 "Hygienic Standards and Requirements for Ensuring the Safety and (or) Harmlessness of Environmental Factors for Humans," water quality indicators are classified into a larger number of types:

1. Epidemiological: microbiological and parasitological;
2. Chemical: generalized, harmful inorganic and organic substances entering the water and formed during its treatment;
3. Organoleptic;
4. Radiation safety

For water intended for various purposes and used in different natural zones, specific requirements and maximum permissible concentrations (MPCs) of pollutants are established. The content of a number of chemical compounds, the number of pathogenic microorganisms (pathogens of intestinal infections, bacteria of the Escherichia coli group), as well as sanitary indicators (permanganate oxidizability) are controlled.

REVIEW OF METHODS FOR STUDYING THE IMPACT OF MEDICAL WASTE ON WATER BODIES

European Community Directive 80/778/EC of July 15, 1980. This document became the basis of water legislation for European countries. The directive proposes assessing water based on organoleptic indicators, physicochemical indicators, the level of toxic substances, and microbiological indicators. Maximum Permissible Concentrations (MPCs) have been established for all of the above-mentioned groups of indicators. In 1998, a new Directive, 98/83/EC, was adopted to replace this Directive. Compared to the previous version, the list of substances for analysis has been reduced, but the requirements have been tightened [5, 6].

The U.S. Federal Standard for Drinking Water Quality [7]. A distinguishing feature of the document is its division into two parts. The first, National Primary Drinking Water Regulations, is mandatory and contains 79 parameters (organic and inorganic impurities, radionuclides, microorganisms) that are potentially hazardous to human health. The second part (National Secondary Drinking Water Regulations) consists of 15 parameters and is advisory in nature; exceeding these standards may worsen the consumer qualities of the water. Maximum Contaminant Levels (MCLs) have also been established for all indicators.

To evaluate the target indicators during the work (Table 1), various analytical methods were analyzed, including physicochemical and biological methods. High-performance liquid chromatography with tandem mass spectrometry (HPLC–MS/MS) demonstrated high selectivity, allowing for accurate determination of substances, but requires expensive equipment [8]. Gas chromatography, on the other hand, allows the analysis of a wide range of analytes, but requires preliminary derivatization of samples [9] and has a higher detection limit compared to HPLC-MS/MS.

Bioassay methods, including the use of daphnia and algae [10], were evaluated as tools for the integral assessment of toxicity, although they are characterized by long duration and provide only qualitative results. Biosensors, in turn, provide the possibility of conducting rapid analysis, but have limitations in selectivity and provide a detection limit in the range of 0.1–1 µg/L

HPLC with tandem mass spectrometry remains the most accurate method, but antibody-based biosensors are promising for mass monitoring.

Researchers from the Technological University Dublin (TU Dublin) presented a review in their work [11] discussing current challenges and promising research directions in the field of water body monitoring. The authors emphasize the importance of improving analytical performance, developing rapid analysis methods, and creating technologies for remote monitoring of water and environmental applications, expressing confidence that their work will contribute to increasing awareness and understanding of the role of advanced analytical methods in protecting the environment and water resources worldwide.

Rastogi et al. [12], in their article published in the Journal of Environmental Management, presented a review of the environmental occurrence, toxicity, and microbial degradation of nonsteroidal anti-inflammatory drugs (NSAIDs). The authors emphasized that NSAIDs are a new class of pollutants due to their incomplete degradation in wastewater treatment plants and their ability to cause physiological problems even at low concentrations. The review examined the presence of diclofenac, ibuprofen, naproxen, and ketoprofen in various aquatic environments, as well as their toxic effects. The authors also analyzed the potential, pathways, and mechanisms of microbial degradation of NSAIDs, noting the role of various enzymes and microorganisms in this process, and identified obstacles to scaling up the process and suggested new research approaches.

Table 1.

Evaluation of analytical methods used for pollution detection

Табл. 1.

Оценка аналитических методов, используемых для определения загрязнений

No.	Method	Advantages	Disadvantages	Detection limit
1	HPLC-MS/MS	Excellent selectivity	Expensive equipment	1–10 ng/l
2	Gas Chromatography	Extensive range of analytes	Requires derivatization (or Requires pre-treatment with derivatization)	10–100 ng/l
3	Biotesting (daphnia, algae)	Integral assessment of toxicity	Long duration (or Lengthy process, Time-consuming)	Qualitative analysis
4	Biosensors	Rapid analysis	Low selectivity	0.1–1 mcg/l

Nevertheless, traditional methods for assessing water quality often do not take into account the interrelationships between various physicochemical indicators, which does not reflect the real picture. Effective assessment should be a multidimensional, interconnected system. One method of statistical assessment that allows for the consideration of such interrelationships is regression modeling.

Regression modeling is widely used in prediction and management tasks. This method is based on the assumption that there is a relationship between external factors and the composition of water that affect a particular variable. Regression analysis is used to determine the type of this relationship. The determination of regression coefficients can be carried out using the least squares method or the maximum likelihood method [13]. In some cases, the principal component analysis (PCA) method is used to predict water quality [14].

Along with the approaches described above, other, less common methods are used in the practice of analyzing and predicting water quality, which, nevertheless, have certain advantages in specific situations.

These methods include:

1. Group Method of Data Handling (GMDH) [15]. This method, developed by Academician A.G. Ivakhnenko, is an algorithm for automatically constructing mathematical models of complex structure based on the principle of self-organization. GMDH allows identifying the most significant factors influencing the target indicator and building models with high forecasting accuracy, especially in limited data conditions [16].

2. Exponential Smoothing of Time Series [14]: This method is used to forecast the values of a time series based on the analysis of its past values. Exponential smoothing allows you to take into account trends and seasonal fluctuations, which is especially important when analyzing the dynamics of changes in water quality indicators.

3. Modeling the Water Treatment Process Using Neural Networks [17]: Neural networks are a powerful tool for modeling complex nonlinear dependencies. The use of neural networks to model the water treatment process makes it possible to take into account a large number of factors that affect the efficiency of treatment and to predict the quality of treated water with high accuracy [18].

In the case of determining pharmaceuticals and their metabolites, their low concentrations (down to 10 ng/L) should be considered. This requires the use of highly sensitive methods, such as high-performance liquid chromatography or tandem mass spectrometry.

Given the wide range of pharmaceuticals, an important task is to identify priority chemical compounds for monitoring. When forming the relevant lists, it is advisable to consider medical-statistical data and information on the commercial demand for drugs [19].

In 2008, a comprehensive method of liquid chromatography – high-resolution tandem mass spectrometry using a chromatography-mass spectrometer was developed at the St. Petersburg Research Center for Ecological Safety, Russian Academy of Sciences, for determining the then-common caffeine, ketoprofen, diclofenac, and ciprofloxacin in natural water [20].

Other methods of determination include hybrid high-resolution mass spectrometry (HRMS) and ultra-high performance liquid chromatography (UHPLC) [21]. All chemical-analytical methods for monitoring the content of pharmaceuticals are highly sensitive but expensive and require the involvement of qualified specialists.

Medical waste remains a serious source of pollution of aquatic ecosystems, contributing to the spread of antibiotic resistance and toxic effects on aquatic organisms.

An effective solution to the existing problem requires a comprehensive approach covering several key areas. First of all, it is necessary to significantly improve analytical control methods that allow for the prompt and accurate identification of the sources and extent of the problem. In parallel with this, modern and effective treatment technologies aimed at minimizing negative impacts should be actively implemented. Finally, it is crucial to tighten regulatory controls, establishing clear frameworks and requirements, as well as ensuring their strict compliance.

APPLICATION OF BIOELECTRONIC SYSTEMS FOR ASSESSING THE CONTAMINATION OF WATER BODIES WITH PHARMACEUTICALS

At the Department of Industrial Ecology of the St. Petersburg State Chemical Pharmaceutical University of the Ministry of Health of the Russian Federation, research is being conducted aimed at developing and applying automated bioelectronic water safety systems. The aim of the research is to assess the reaction of these bioelectronic systems to sudden changes in water composition caused by the entry of pharmaceuticals and their metabolites.

Representatives of crustaceans (Crustacea, Decapoda), specifically the crayfish Astacus leptodactylus, found in low-polluted areas of rivers and lakes in the Northwest of Russia, particularly in the Neva River basin, are used as test organisms-bioindicators.

One promising approach to monitoring the contamination of aquatic environments is the use of a biological monitoring method based on recording the physiological activity of a living organism-indicator. This method, described in RF Patent No. 2461825 C1 (Kholodkevich S. V., Ivanov A. V. "Method for Biological Monitoring of the Environment and System for its Implementation") [22], involves placing an animal with a physiological activity sensor in a controlled environment, simulating a daily cycle of illumination, converting the electrical signal reflecting physiological activity into digital form, determining the statistical characteristics of the signal, and comparing them with threshold values to generate an environmental hazard signal.

In the context of monitoring pharmaceuticals and their metabolites, this method can be adapted to detect specific responses of the indicator organism to the exposure of these compounds, which in turn will allow the development of theoretical approaches to substantiate hygienic standards for controlling the presence of these compounds in the water of centralized drinking water supply systems.

In this work, various research methods on the impact of medical waste on the environment were considered. All these methods provide important information on the impact of medical waste on the environment and human health. It is necessary to develop new legal documents regulating the list of pharmaceuticals to be monitored and to update methods for determining medical preparations in water bodies.

The results of the analysis indicate the need to develop and implement an effective set of measures aimed at preventing environmental pollution by medical waste. In our opinion, this set of measures should include the following elements:

1. Ensuring proper disposal of medical waste in accordance with current legislation. Goal: Minimizing the risks of environmental pollution during disposal.

2. Gradual transition to the use of environmentally friendly materials that do not contain hazardous chemicals in medical institutions. Goal: Reducing the volume of hazardous waste requiring special disposal.

3. Systematic training of medical personnel on the rules for the safe handling of medical waste. Goal: Preventing errors and violations that lead to environmental pollution and health risks.

Only a comprehensive implementation of these measures will achieve a significant reduction in the negative impact of medical waste on the environment and public health.

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Анализ негативного воздействия медицинских отходов на водные объекты – растущая угроза для водных ресурсов и здоровья населения

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АННОТАЦИЯ. В представленной работе проанализированы литературные источники о методах утилизации медицинских отходов и оценке их воздействия на водные объекты в контексте существующего нормативно-правового поля. Актуальность темы обусловлена ростом объемов этих отходов и их потенциальной опасностью для населения и экосистем. Цель работы – систематизация и оценка подходов к утилизации и методов анализа загрязнения водных объектов. Работа выполнена в рамках научно-исследовательской темы кафедры промышленной экологии, направленной на разработку теоретических подходов к обоснованию санитарных нормативов содержания лекарственных средств и их метаболитов в питьевой воде. Определение степени опасности медицинских отходов, являющееся результатом данного исследования, необходимо для разработки обоснованных и эффективных стратегий снижения их негативного воздействия на окружающую среду и здоровье человека. Приобретенное понимание проблемы служит прочной основой для дальнейших исследований, направленных на совершенствование методов управления и обезвреживания медицинских отходов.

КЛЮЧЕВЫЕ СЛОВА: медицинские отходы; обращение с отходами производства и потребления; негативное воздействия на окружающую среду; лекарственные средства; питьевая вода; загрязнение водных объектов

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Авторы заявляют, что у них нет конфликта интересов.

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