MODERN APPROACHES TO WASTEWATER TREATMENT FROM PESTICIDES: A LITERATURE REVIEW

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The article presents a review of modern technologies for the treatment of wastewater contaminated with pesticides — persistent organic pollutants that exert a long-term toxic impact on ecosystems and human health. Due to their high stability, bioaccumulation potential, and low biodegradability, the presence of pesticides in aquatic environments poses a serious environmental problem, necessitating the implementation of effective wastewater treatment solutions. The focus is placed on four main groups of methods: oxidative, sorptive, biological, and combined approaches. Oxidative methods include ozonation, ultraviolet (UV) treatment, photocatalysis, and the Fenton process. These technologies are effective in decomposing persistent organic compounds but often require significant energy input. Sorptive methods — using activated carbon, zeolites, graphene-based materials, etc. — are characterized by high availability and simplicity in application, yet they require further regeneration or disposal of the sorbents. Biological methods, such as those involving activated sludge, biofilms, and microalgae, are environmentally friendly but limited in their ability to degrade poorly biodegradable substances. The most promising direction is recognized as the application of combined approaches that integrate the advantages of different methods while mitigating their drawbacks. Particular attention is given to the synergistic use of ozonation, UV treatment, Fenton processes, and biosorption. Such integrated systems can achieve a high degree of purification while reducing energy consumption and operational costs. It is substantiated that further development of combined technologies is a key direction for enhancing the efficiency of wastewater treatment from pesticides.

Keywords: *biodegradation, biosorbents, Fenton process, pesticides, sorption, wastewater*

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1. Introduction

Modern methods of wastewater treatment from pesticides and toxic chemical compounds use sophisticated physical, chemical, and biological technologies. These advanced approaches can effectively reduce the toxicity and concentration of pollutants to environmentally safe levels, making them key tools for environmental protection.

The main technological solutions include oxidation, sorption, and bioremediation processes. Activated carbon-based materials are central to the adsorption of pesticides, providing a high level of removal from the aquatic environment. At the same time, biological treatment methods, due to their complex mechanisms, demonstrate a wide potential for the destruction of persistent pollutants.

Especially important is the use of bioreactors that use sequential aerobic and anaerobic biochemical processes. Bioreactors are highly efficient due to the use of activated sludge and optimized bio-oxidation protocols. This approach can significantly improve the quality of treatment even in the presence of complex pollutants.

Researchers are actively developing comprehensive deep cleaning technologies. Such approaches include coagulation, flotation, and ion exchange mechanisms.

The use of such technologies contributes to the development of ecosystems and effective water management, making them indispensable in the face of global environmental challenges.

2. Water purification from pesticides by oxidation technologies

Persistent organic pollutants, even in low concentrations, have genotoxic, immunotoxic and carcinogenic effects, as well as adversely affect human reproductive function, which poses a real threat to the health of present and future generations (Кофман, 2012).

This problem is recognized as a global environmental threat that requires immediate measures to address it (Кофман, 2012).

In this regard, on May 22, 2001, the Stockholm Convention was adopted in Stockholm and entered into force on May 17, 2004. The main objective of the Convention is to protect the environment and human health from persistent organic pollutants (Кофман, 2012).

According to the Stockholm Convention, the list of persistent organic pollutants includes nine organochlorine pesticides: aldrin, chlordane, dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, and DDT. These pesticides are characterized by high toxicity, resistance to degradation in natural conditions, and the ability to bioaccumulate in food chains (2006).

To purify water from such pollutants, the most effective are advanced oxidation technologies that provide destructive destruction of persistent organic compounds (2006).

Oxidative technologies such as ozonation, the Fenton process (Fe(II)/Fe(III) using H2O2), photolysis with ultraviolet radiation (UV), combinations of UV with H2O2 or O3 (photo-ozonation), and electrochemical oxidation are promising methods for the destruction of persistent organic pollutants.

Paper (Гончарук, 2003) investigated the efficiency of purification of a model solution containing atrazine and pesticides using sequential ozonation and UV irradiation. The treatment lasted 15 minutes, providing 94% removal of pollutants (Гончарук, 2003).

However, the low solubility of ozone in water is a limiting factor for such processes.

The destruction of the pesticide acetochlor was studied under direct ozonation conditions in (Kene, 2004), which showed that at a partial pressure of O3 of 488 Pa, a concentration of acetochlor of 100 mg/L and a temperature of 47 °C, the complete destruction of the pesticide occurred in 40 minutes (Kene, 2004).

The authors of (Hai-Yan, 2004) presented the results of studies in which alachlor (ALC) was destroyed by ozonation. 0-12.5 mg/L (Hai-Yan, 2004).

The process was carried out in a 70×300 mm column with a gas flow rate of 30 mL/min and ozone production of 1.68 mg/min (Hai-Yan, 2004).

It was found that the destruction of alachlor (ALC) mainly occurs due to the action of OH radicals, while the role of direct contact of ALC molecules with ozone is minimal (Hai-Yan, 2004).

The optimal conditions for the process include concentrations of Fe^{2+} and Mn^{2+} of 0.5 mg/L and humic substances of 5 mg/L, which ensures the removal of about 80% of ALC (Hai-Yan, 2004).

In (Gunes, 2006), the effect of various methods of wastewater treatment containing pesticides on their toxicity and biodegradability was studied. Among the methods considered, the combination of ozonation and coagulation proved to be the most effective (Gunes, 2006).

It was found that their combined use provides a synergistic effect, reducing the toxicity of wastewater by 24% or more, as well as improving biodegradability. The study also provides the values of oxidation rate constants during ozonation (Gunes, 2006).

The pilot experiment described in (Maldonado, 2006) involved the development of a method for treating wastewater containing a mixture of pesticides (alachlor, atrazine, chlorphenvinphos, diuron, and isoproturon) and pharmaceutical products. The removal of contaminants was achieved by combining ozonation with subsequent biodegradation, which provided deep purification (Maldonado, 2006).

Study (Yan-jun, 2006) focuses on the problem of persistent and toxic substances entering natural water sources, such as pesticides, which need to be removed during the preparation of drinking water (Yan-jun, 2006).

In particular, the destruction of benzophenone (BP) at a concentration of 10 mg/L was studied. The process was carried out in a 3-liter reactor with a ceramic surface impregnated with manganese, iron, and potassium compounds, which provided high catalytic activity (Yan-jun, 2006).

As a result of the complex effect of ozone and catalysts, 90% destruction of BF was achieved (Yan-jun, 2006).

The authors of (Yan-jun, 2006) studied various methods of destruction of diazinon (DZ), an organophosphate insecticide that is a hazardous pollutant of natural water sources, in laboratory conditions. Methods such as UV irradiation, ozonation, Fenton's reagent, and their combinations were investigated: UV + H_2O_2, O_3 + H_2O_2, and Fenton's reagent + UV (Yan-jun, 2006).

It has been established that in all cases, the mechanisms of destruction of DZ are different and the efficiency of its removal is determined by the total concentration of hydroxyl radicals and other oxidizing agents (Yan-jun, 2006).

Imidacloprid, a drug widely used in agriculture, was taken for the experiments (Yan-jun, 2006).

Imidacloprid is a new-generation systemic insecticide belonging to the chemical class of nitrogen-containing heterocyclic pesticides.

Toxicological and hygienic characteristics (Yan-jun, 2006):

- carcinogenicity (Yan-jun, 2006);
- endocrine disorders (Yan-jun, 2006);
- reproductive toxicity, teratogenic effect (Yan-jun, 2006);
- acetylcholinesterase inhibition (Yan-jun, 2006);

- neurotoxicity, skin, eye, and respiratory tract irritation (Yan-jun, 2006).

- WHO classification - II hazard class (moderately hazardous) (Yan-jun, 2006).

Physical and chemical properties:

- solubility in water at 20Co - 610 mg/l (high) (Yan-jun, 2006);

- half-life in soil, according to EU laboratory studies, is 77-341 days (stable) (Yan-jun, 2006);

- aqueous photolysis at pH 7 (DT50) - 4.7 days (Yan-jun, 2006);

- aqueous hydrolysis at 20Co and pH 7 - stable (very stable) (Yan-jun, 2006).

Imidacloprid is used in a number of domestic medicines, including Tanrek, Corado, Confidor Extra, Iskra Zolota, Zubr, Colorado, Coginor, Warrant, Biotlin, Commander, Tabu, Chinook, Prestige, and others. Among the Polish analogs, we can distinguish such preparations as Nuprid, ProAgro, Gaucho Mospilan 20SP, Calypso 480 SC, Montur 190FS, and Chinook (Yan-jun, 2006).

To analyze the content of imidacloprid, a spectrophotometric method was used using a scanning spectrophotometer SF-2000 operating in the ultraviolet range. The maximum absorption of the substance was observed at a wavelength of 270 nm (Yan-jun, 2006).

As part of the experiments, various methods of intensifying water purification from imidacloprid using improved oxidation technologies were studied. Among these methods were hydrogen peroxide treatment in the presence of catalysts, direct ozonation, and ultraviolet irradiation. Experiments with hydrogen peroxide were carried out at pH values ranging from 2 to 10 and using catalysts such as titanium dioxide (TiO_2), manganese dioxide (MnO_2) and iron (II) salts (Yan-jun, 2006).

However, no change in the concentration of imidacloprid in solution was recorded.

In the study of the direct ozonation me, an imidacloprid solution with a concentration of 20 mg/L was used, and the ozone dose was also 20 mg/L, which corresponds to a 1:1 ratio (Yan-jun, 2006).

The concentration was monitored using a spectrophotometer in the ultraviolet range. Within 5 minutes, the purification showed an efficiency of about 40% (Yan-jun, 2006).

The aim of the study was also to investigate the kinetics of imidacloprid degradation under UV radiation. %. slowed down, which is associated with a decrease in the probability of interaction of light quanta with the molecules of the starting substance at low concentrations (Yan-jun, 2006).

The results of the study confirmed that the photolysis of imidacloprid under the influence of UV radiation is quite fast, which makes it possible to use this method for water treatment in flow-through installations (Yan-jun, 2006).

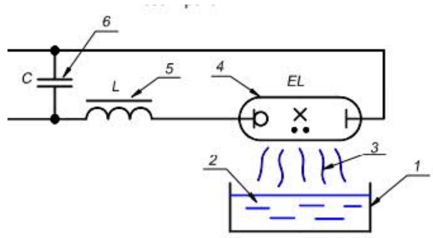

Fig. 1. *Installation diagram:*
1 – Petri dish; 2 – imidacloprid solution; 3 – ultraviolet radiation; 4 – DRL-250 quartz lamp; 5 – throttle; 6 – capacitor

3. Biosorption Composite for Pesticide Detoxification in Soils

The impact of pesticides on soil microorganisms and their microbial degradation processes is one of the key topics of both foreign and domestic research in the field of soil microbiology. Based on the analysis of the scientific literature, the need to develop biosorption complexes in which microorganisms-destructors are fixed on carriers that have sorption activity towards pollutants (pesticides) and biocompatibility with the microorganisms themselves is substantiated (Калюжин, 2009).

The results of studies on the impact of pesticides on soil microorganisms and their ability to decompose such substances have revealed a lack of information on the formation of the soil microbial community at high levels of pesticide contamination. This is especially true for areas where storage facilities with unusable pesticides are located (Калюжин; 2009).The main focus of the research was on studying the impact of various pesticides on the number, species composition, structural changes in soil microflora, as well as on the degree of their sensitivity to chemicals (Real, 2007; Калюжин, 2009).

The impact of various pesticides on soil microorganisms and their ability to microbial degradation is being actively studied by modern Ukrainian scientists (Ігнатович, 2008; Хохлов, 2014).

Preliminary studies on the identification of microorganisms-biodestructors of pesticides were presented in the works of A.B. Kolupaev (Анан'єва, 2003).

One of the most urgent tasks in this area is the creation of biological products based on strains of xenobiotic biodegraders isolated from natural aboriginal microflora (Анан'єва, 2003).

Of particular scientific and practical interest is the development of technologies for the use of such biological products, including biosorption complexes for remediation of pesticide-contaminated soils. These developments take into account the interaction of biological products with natural microflora, as well as the impact of climatic and anthropogenic factors (Анан'єва, 2003).

The research methodology was based on the works of domestic and foreign authors on the isolation of microorganisms-destructors from pesticide-contaminated soils and the assessment of their destructive potential. The conditions of cell immobilization on different types of sorbents, biotechnological methods of growing microbial biomass, and methods of introducing biosorption composites into contaminated soils were studied (Анан'єва, 2003).

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Preliminary studies on the detection of microorganisms-destructors of pesticides were presented in the works of A.B. Kolupaev (Анан'єва, 2003).

One of the most pressing tasks in this field is the creation of biological products based on strains of microorganisms that destroy xenobiotics, isolated from natural indigenous microflora (Анан'єва, 2003).

Of particular scientific and practical interest is the development of technologies for the application of such biological products, including biosorption complexes for the remediation of pesticide-contaminated soils. These developments take into account the interaction of biological products with natural microflora, as well as the influence of climatic and anthropogenic factors (Анан'єва, 2003).

The research methodology was based on the works of domestic and foreign authors on the isolation of destructive microorganisms from soils contaminated with pesticides and the assessment of their destructive potential. The conditions for cell immobilization on different types of sorbents, biotechnological methods for growing microbial biomass, and methods for introducing biosorbent composites into contaminated soils were studied (Анан'єва, 2003).

These approaches ensured the high reliability of results and objectivity of conclusions (Анан'єва, 2003).

The research analyzed plant waste, carbon materials, natural mineral sorbents, biosorption complexes, pesticides, soils, and agricultural products (Анан'єва, 2003).

Soil samples were collected and microbiologically analyzed in accordance with generally accepted soil microbiology methods (Анан'єва, 2003).

The number of soil microorganisms of different groups was determined by the method of sowing dilutions of soil suspensions on selective nutrient media (Анан'єва, 2003).

Microorganism cultures belonging to the genera Pseudomonas, Bacillus, Penicillium, Emericella, Coniophora, and Rhizobium were isolated from the soils (Mykolaiv region, Pervomaisky district) (Анан'єва, 2003).

To identify biodegrading microorganisms, the method of cumulative cultures on chernozem soils contaminated with pesticides was used (Анан'єва, 2003).

The natural microflora of these soils were found to be adapted to local climatic conditions, stable, and have a synergistic effect (Анан'єва, 2003).

In addition, the return of microbial complexes to the natural environment gives them a selective advantage, enhancing their ability to destroy pesticides (Анан'єва, 2003).

Pesticides were used as the sole source of carbon and energy (Анан'єва, 2003):

- betanes – (fenmydifam) (Анан'єва, 2003);
- Caribu – (triflusulfuron-methyl) (Анан'єва, 2003);
- Pyramine – Turbo – (chloridazon) (Анан'єва, 2003);
- Nurel-D – (chlorothifos cypermethrin) (Анан'єва, 2003);

- PCB – (polychlorinated biphenyl) (Анан'єва, 2003).

Each sample of contaminated soil was placed in a flask with a nutrient medium and pesticide, where microorganisms were grown under constant stirring and at a temperature of 25–30 °C (Анан'єва, 2003).After that, the culture fluid was transferred to a fresh nutrient medium of similar composition for re-cultivation in the presence of pesticide (Анан'єва, 2003).

At the next stage, microbial cells were sown on dense nutrient media (based on agar-agar), which were then used to immobilize destructive microorganisms on the surface of the sorption carrier (Анан'єва, 2003).

The process of pesticide destruction was studied both on contaminated soils and in an aquatic environment using destructive microorganisms in the form of culture fluid or immobilized on a sorbent (Анан'єва, 2003).

The concentration of pesticides in the soil was determined using high-performance liquid chromatography (HPLC) and gas-liquid chromatography methods, which are widely used in environmental analytical chemistry (Анан'єва, 2003).

The biodegradative capacity of the sorbent with immobilized microorganisms was monitored by measuring the decrease in pesticide concentration and the accumulation of microbial biomass (Анан'єва, 2003).

To assess the degree of destruction, the redox indicator triphenyl tetrazolium chloride (TTC) was used, which, when interacting with microbial dehydrogenase, forms reduced triphenylformazan (TFF), coloring the system red, which indicates the reproduction of microorganisms and their active destructive activity (Анан'єва, 2003).

A qualitative assessment of the ability of microorganisms to destroy pesticides was carried out visually in terms of changes in dehydrogenase activity and the growth zone of microorganisms (Анан'єва, 2003).

It has been proven that almost all pesticides can be utilized by microorganisms (Анан'єва, 2003).

At the same time, the immobilization of microbial cells on a sorption carrier significantly increased their destructive efficiency due to the adsorption of pollutants (Анан'єва, 2003).

Carbon materials, plant sorbents (peat, crushed straw, beet pulp, bagasse), as well as mineral materials such as kaolin and vermiculite were studied as sorbents for the immobilization of microorganisms (Анан'єва, 2003).

The most effective sorbent was a composite consisting of crushed wheat straw, peat, and beet pulp (Анан'єва, 2003).This plant-based carrier demonstrated not only high adsorption capacity but also biocompatibility, activating the destructive properties of microorganisms (Анан'єва, 2003).

The studies were conducted on the model and real "soil-water-pesticide" systems, where pyramid-turbo (chlorination) and natural-D (chlorpyrifos cypermethrin) were used as pesticides in various concentrations (Анан'єва, 2003).

The effectiveness of sorption-destructive materials was tested in laboratory conditions by monitoring the residual content of pesticides in the aquatic environment, on the carrier, and in the soil (Анан'єва, 2003).

The immobilization of microorganisms on the sorbent made it possible to create biodegradative materials that simultaneously sorbed pollutants and decomposed them, ensuring effective bioremediation (Анан'єва, 2003).

Straw is an active absorber of organic pollutants, serves as a carrier of microorganisms, and is a source of the enzyme yellow laccase, which triggers the destruction of pesticides. Peat acts as a preservative for microorganisms and is also a source of organic matter. Beet pulp (or bagasse, a waste product of sugar production) acts as a source of polysaccharides, retains moisture, and provides optimal humidity for microbial processes, accounting for up to 1/5 of the composite's mass (Анан'єва, 2003).

The destructive activity of such complexes reached 90% during the decomposition of pesticides (Анан'єва, 2003).

The introduction of biosorbent material into pesticide-contaminated soil allowed the detection of structural changes in pesticides. These changes were recorded using IR spectrum analysis, which showed qualitative and quantitative changes indicating a restructuring of the chemical structure of the contaminant (Анан'єва, 2003).

According to high-performance liquid chromatography (HPLC) data, within 30 days, the initial concentration of the pesticide in the soil decreased to 30%, and over a longer period, complete destruction of the pollutant structure was recorded (Анан'єва, 2003).

The greatest efficiency of biodegradation processes was observed in soils with slightly acidic and neutral pH levels (6–7), which include chernozem (Анан'єва, 2003).

The optimal moisture content for microorganisms to function is 50–70% of the soil's total moisture capacity. This moisture content is effectively maintained by a component of the composite—beet pulp (Анан'єва, 2003).

Table 1. *Destructive activity (Анан'єва, 2003).*

Time since treatment start	Variant of MO-destructor application			
	MO in free state (culture liquid)		Immobilized MO on sorbent material (composite)	
	Chloridazon	Chlorpyrifos	Chloridazon	Chlorpyrifos
Initial	50.0	30.0	50.0	30.0
After 10 days	49.2	25.0	44.0	21.0
After 30 days	42.0	21.0	29.0	12.0
After 40 days	38.0	18.0	24.0	8.0
After 50 days	36.5	17.2	21.0	4.0
After 60 days	32.0	16.4	18.0	3.0
After 80 days	25.0	15.0	9.0	1.0
After 100 days	21.0	14.0	6.0	0.6
After 120 days	14.9	14.0	0.4	0.4

The practical significance of the developed biosorption technology using a detoxifying agent has been confirmed by the results of production tests. They were conducted both in agricultural fields of agro-industrial complexes and in particularly contaminated areas, including abandoned unauthorized warehouses with unidentified pesticides (Анан'єва, 2003).

Based on the data obtained, practical recommendations for the use of this complex action preparation were formulated (Анан'єва, 2003).

The effectiveness of the biosorption preparation depends on the method of its application. Soil purification and pesticide neutralization are carried out after their target action is completed. The main part of the preparation is applied by row application followed by abundant watering, except in cases where the soil is already moist or an irrigation system is used (Анан'єва, 2003).The depth of application of the preparation is important and should coincide with the soil layer where the main mass of the roots of the agricultural crop is located. This ensures maximum effectiveness and safety of use (Анан’єва, 2003).

Incorrect or excessive doses of the preparation can disrupt the natural biocenosis of the soil, so adherence to the dosage is strictly mandatory. The recommended application rate is 0.2–0.3 kg of the product per 1 m2 of soil. At the same time, the product is environmentally safe and does not cause soil mineralization (Анан’єва, 2003).

The greatest effectiveness is achieved when used as part of a biosorption complex of sorption materials based on plant raw materials.

4. Treatment of wastewater containing organic impurities

Organic pollutants enter the environment through wastewater generated by industrial, agricultural, and municipal activities. Wastewater from agricultural facilities often contains high concentrations of pesticides and herbicides, wastewater from coking plants contains polycyclic aromatic hydrocarbons, and the chemical industry pollutes water with heterogeneous compounds such as diphenyl polyphenol esters and polychlorinated biphenyls. Wastewater from the food industry includes complex organic pollutants with high biochemical oxygen demand (BOD), while domestic wastewater contains oils, pharmaceutical compounds, dissolved organic matter, and surfactants (Колупаєв, 2009).

The most widely used method of domestic wastewater treatment is biological treatment. This method is used in most treatment plants in Ukraine and around the world due to its effectiveness. However, the traditional treatment scheme (“aerotank – secondary clarifier”), common in most Ukrainian plants, has significant drawbacks. First of all, it provides effective removal of nitrogen and phosphorus from water (Колупаєв, 2009).

The main reason for its inefficiency is considered to be the use of outdated technologies. To eliminate this problem, a modernization option was proposed, which consists of replacing secondary clarifiers with combined aeration tanks and clarifiers. This eliminates the need for classic aeration tanks (Колупаєв, 2009).

The advantages of the new technology include (Клименко, 2016):

- a significant reduction in air consumption for aeration of the water-sludge mixture (by 4 times), which leads to energy savings (Клименко, 2016);

- improvement of the quality of treated water in terms of phosphate, nitrogen, and other pollutants due to an increase in the concentration of activated sludge (Клименко, 2016);

- freeing up significant land areas by eliminating classic-type aeration tanks (Клименко, 2016).

Methods for treating wastewater with organic pollutants can be divided into three groups (Клименко, 2016):

Reagent methods – coagulation, electrocoagulation, pressure flotation.

Sorption and separation methods – the use of activated carbon, ion exchange materials, ultrafiltration, reverse osmosis, foam separation, and electroflotation (Клименко, 2016).

Destructive methods of oxidation and reduction, ensure the deep decomposition of organic substances. These methods include treatment with chlorine, ozone, and hydrogen peroxide, as well as electrochemical and electrocatalytic oxidation (Клименко, 2016).

Electrochemical oxidation is a powerful tool that allows for the complete mineralization of organic matter that is not subject to biodegradation. It also allows organic substances to be extracted with minimal structural changes, returning them to production (Клименко, 2016).

Modern developments actively use indirect electro-oxidation processes, including the electro-Fenton process. This method, using boron-doped diamond anodes (BDD), is highly efficient, reducing chemical oxygen demand (COD) by 85–100% (Клименко, 2016). An important direction for further development is the integration of the electro-Fenton process with other technologies, such as photoelectro-Fenton, sonoelectro-Fenton, and peroxyelectrocoagulation, which provides a synergistic effect in wastewater treatment (Клименко, 2016).

To reduce energy consumption, which is the main drawback of electrochemical methods, advanced electrochemical oxidation processes are used. They combine anodic and cathodic generation of hydroxyl radicals, which increases efficiency and reduces energy consumption (Савелова, 2005).

5. Research into methods for cleaning technological equipment used in pharmaceutical and chemical production using a micellar decontamination system

The issue of neutralizing organophosphorus compounds (OPCs) used in chemical weapons, pesticides, pharmaceutical products, and highly toxic chemicals is becoming increasingly relevant. This problem is directly related to the tightening of environmental safety requirements at the global level [18, 19]. Active research in this area began after the signing of the 1993 international Convention on the Prohibition of Chemical Weapons, which obliges participating countries to destroy their declared chemical weapons stockpiles (Петров, 1993).

Among the various technologies for the disposal and decomposition of OCS, three main groups of methods stand out: chemical, thermal, and biological. These approaches are widely used in industry to eliminate major OCS such as sarin (GB), soman (GD), VX gas, metaphos, chlorophos, and their derivatives (Петров, 1993; Vakhitova, 2017).

Key technologies used in chemical decomposition include:

hydrolysis using aqueous alkali solutions;

Oxidative chlorination with a mixture of chlorine lime and calcium hypochlorite;

Alcoholysis using monoethanolamine or potassium butylate, followed by thermal bitumenization of the resulting salt concentrates and their subsequent disposal (Vakhitova, 2017).

However, these technologies have a number of significant drawbacks. Among them are the periodicity of technological processes, the high aggressiveness of the media used, which leads to corrosion of equipment, as well as the significant formation of contaminated wastewater (Vakhitova, 2017).

In addition, the reagents used, such as alkalis, alkali metal alcoholates, and monoethanolamine, have low reactivity with phosphoric and phosphonic acid esters (Vakhitova, 2017).

Due to the low solubility of organophosphorus compounds in water and the limited effectiveness of reagents, the detoxification process requires high temperatures and the use of high concentrations of active substances. In this regard, one of the main tasks in the development of new methods for the destruction of FOS is the creation of systems based on mild reagents, characterized by a high degree of environmental safety and ensuring economic efficiency (Vakhitova, 2017).

One of the priority areas of research has been the creation of universal systems based on an oxidative-nucleophilic mechanism of action. These systems ensure the rapid and irreversible destruction of toxic substances of various natures (Vakhitova, 2017).

From a practical point of view, methods using hydrogen peroxide (H_2O_2) are particularly attractive. The hydroperoxide anion (HOO^-) formed in such systems is one of the most active α-nucleophiles (Савелова, 2005; Симаненко, 2002; Попов, 2000; Соломойченко, 2006), while H_2O_2 itself has relatively weak oxidative activity (Richardson, 2000; Yao, 2003; Вахітова, 2018).

To increase the reactivity of hydrogen peroxide, acid activators are used to convert it into peroxyacids (Richardson, 2000; Wagner, 2002).

Of particular interest in the context of industrial and environmental safety is the technology of H_2O_2 activation by hydrocarbonate ions and boric acid derivatives (Іггатович, 2008; Richardson, 2000).

To determine the concentration of dimethoate in solutions, a validated HPLC method was used (Вахітова, 2018):

Analytical column: Kinetex® 5 µm EVO C18 100 Å, LC Column 150 * 4.6 mm.

Chromatographic conditions:

- Mobile phase: acetonitrile: acetic acid solution (pH = 3.5) = 40:60
- Flow rate: 1 cm3/min
- Solvent: acetonitrile
- Column thermostat temperature: 40 °C
- Injector thermostat temperature: 20 °C
- Injection volume: 5 µl
- Detection wavelength: PDA, λ = 210 nm

As part of the validation of the method used to determine the concentration of dimethoate in solution, the limit of quantification of the substance was set at 15 ppm. According to the data obtained, the time required to decontaminate a contaminated solution with a dimethoate concentration of about 3000 ppm to a level below the limit of quantification is 120 minutes. This indicator is acceptable for the cleaning of technological equipment in chemical production (Вахітова, 2018).

The developed micellar decontamination system based on a solid source of hydrogen peroxide is suitable for cleaning technological equipment in model production using the active ingredient dimethoate. The time required to reduce the concentration of dimethoate from 3000 ppm to below the limit of quantification is also 120 minutes (Вахітова, 2018).

Future research aimed at testing a micellar decontamination system for organophosphorus compounds based on a solid source of hydrogen peroxide will focus on the decontamination of substances that contaminate technological equipment in various processes at pharmaceutical and chemical enterprises (Вахітова, 2018).

An analysis of modern wastewater treatment methods has shown that the most effective methods for removing persistent organic pollutants are oxidative technologies, in particular photocatalytic methods, ozonation, Fenton processes, and their modifications.

These methods demonstrate high efficiency due to the generation of active radicals capable of completely destroying organic pollutants.

6. Conclusions

The study of the effect of combined oxidation processes on various organic impurities has demonstrated the ability to destroy even persistent substances such as pesticides, benzophenone, and diazinon.

This confirms the feasibility of introducing such technologies in industrial treatment facilities.

Thus, the results of the study demonstrate the effectiveness and feasibility of introducing modern combined technologies for wastewater treatment, which allow achieving a high level of environmental safety, reducing the toxicity of pollutants, and improving the quality of treated water.

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СУЧАСНІ ПІДХОДИ ДО ОЧИСТКИ СТІЧНОЇ ВОДИ ВІД ПЕСТИЦИДІВ: ЛІТЕРАТУРНИЙ ОГЛЯД

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У статті подано огляд сучасних технологій очистки стічних вод від пестицидів — стійких органічних забруднювачів, які виявляють тривалий токсичний вплив на екосистеми та здоров'я людини. Через їх високу стабільність, здатність до біоакумуляції та низьку біодеградацію, наявність пестицидів у водних об'єктах становить серйозну екологічну проблему, що вимагає впровадження ефективних рішень у сфері водоочищення. Основну увагу зосереджено на чотирьох основних групах методів: окислювальних, сорбційних, біологічних та комбінованих. До окислювальних належать процеси озонування, ультрафіолетова (УФ) обробка, фотокаталіз, а також метод Фентона. Ці технології ефективні щодо розкладу стійких органічних сполук, однак потребують значних енергозатрат. Сорбційні методи — із застосуванням активованого вугілля, цеолітів, графенових матеріалів тощо — характеризуються високою доступністю й простотою реалізації, але вимагають подальшої регенерації чи утилізації сорбентів. Біологічні методи, зокрема з використанням активного мулу, біоплівок та мікроводоростей, є екологічно безпечними, однак обмежені щодо малобіодеградованих речовин. Найперспективнішим напрямом визнано комбіновані підходи, які поєднують переваги різних методів і нівелюють їх недоліки. Особливу увагу приділено синергетичному використанню озонування, УФ-обробки, процесів Фентона та біосорбції. Такі інтегровані системи дозволяють досягти високого ступеня очистки при зниженні енергоспоживання та операційних витрат. Обґрунтовано, що подальший розвиток комбінованих технологій є ключовим напрямом у підвищенні ефективності очистки стічних вод від пестицидів.

Ключові слова: *біодеструкція, біосорбенти, пестициди, сорбція, стічні води, Фентон*