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Review

Current Status and Trends in Environmental Biotechnology

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Abstract: To achieve the goals of sustainable development of the world community, it is necessary to ensure the protection, restoration of ecosystems and promotion of their rational use, termination of the process of land degradation and prevention of reduction of biological diversity. The review analyzes a large volume of scientific publications and considers modern trends in the development of biotechnological approaches for cleaning soil, water and air from various pollutants, including persistent and hazardous ones. A separate chapter is devoted to the utilization and cleaning of aquatic and terrestrial ecosystems from synthetic materials, including microplastics. Attention is paid to environmental technologies used for reclamation of contaminated military facilities. The purpose of this review was to analyze and summarize modern methods, as well as to characterize the main directions of modern environmental biotechnology.

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Contents

Introduction

The population of our planet grew at an ever-increasing rate until 2000. By now, the population has crossed the threshold of 8 billion people. According to the UN forecast, the population of the Earth by 2150 will reach a permanent limit of 11-12 billion people. With the processes of urbanization, industrialization, development of mineral resources and new lands, problems of preserving the environment for future generations arise. In the 20th century, humanity began to seriously think about the scale of damage caused to the environment. Requirements for environmental protection have changed significantly, becoming an important part of not only interstate relations, but also a fundamental element of the strategies of the world's leading corporations.

In 2015, the UN General Assembly adopted the Concept of sustainable development (Sustainable Development Goals), a set of measures aimed at meeting current human needs while preserving the environment and resources, i.e. without compromising those of future generations, as a “plan to achieve a better and more sustainable future for all” (A/RES/71/313, 2017). These goals were called the "2030 Agenda" in the General Assembly resolution [1]. The concept of sustainable development includes protecting, restoring and promoting sustainable use of terrestrial ecosystems, sustainable management of forests, combating desertification, halting and reversing land degradation and preventing loss of biodiversity.

Currently, significant efforts are being made globally to develop and disseminate environmental strategies, with particular attention to biotechnological methods. These modern approaches are divided into two key areas: waste recycling - their biotechnological transformation and utilization, and bioremediation, which means the restoration and purification of soil, water resources and the atmosphere.

Ecological biotechnology is the use of biological processes and systems to improve the quality of the environment and ensure rational use of natural resources. Eco-biotechnology is aimed at solving environmental problems, such as cleaning soil, water, air from pollution and recycling various wastes. Technological innovations applied in the areas of wastewater treatment, air pollution control, land reclamation and the synthesis of alternative energy sources are key elements in the development of ecological biotechnology. The integration of biologically based methods into various industrial processes contributes to the creation of environmentally friendly production.

Environmental or green biotechnology can play a significant role in developing sustainable energy solutions. One example is the use of anaerobic digestion, a biotechnological process that converts organic waste into biogas. This biogas can then be used to generate electricity or as renewable natural gas. In collaboration with renewable energy companies, eco-biotechnology can help improve the efficiency and scalability of these processes.

Environmental biotechnology can also contribute to sustainable agriculture through various applications. One such application is bioremediation, which can help clean up contaminated soil and make it suitable for agriculture. In addition, biotechnological processes can improve nutrient cycling and soil fertility, leading to healthier and more productive crop growth. In the agricultural sector, environmental biotechnology can help to adopt these practices and integrate them into sustainable farming systems.

Currently, there is increased interest in eco-biotechnology in various regions of the world. Thus, in the countries of the Asia-Pacific region, particular attention is paid to such pressing issues as water scarcity. In the area of protecting ecosystems in the North American continent, particular preference is given to technological developments in the sector of water purification, waste management and energy generation from renewable sources, with a key role played by reputable companies and research centers under the auspices of government programs aimed at supporting environmentally friendly technologies. The European eco-biotechnology market has demonstrated significant growth, mainly due to the systematic governmental support for scientific research and development, and simultaneously due to a strict adherence to eco-standards. Close attention is paid to the development of bioremediation, control of atmospheric pollution and optimization of the use of renewable energy sources. Progress in the Latin American eco-biotechnology segment is being achieved due to the optimization of water resources management, waste disposal and organic agriculture. The Middle East and Africa are showing growing interest in eco-biotechnology practices, focusing on rational water management, waste recycling and active implementation of renewable energy sources.

Key foreign companies working in the field of environmental biotechnology include: Thermo Fisher Scientific Inc., Danaher Corporation, Merck KGaA, Suez SA, Ecolab Inc., Genomatica, Novozymes, LanzaTech, Alken–Murray, Agilent Technologies Inc. The largest global achievements in 2022 include the developments by Enzytech in the field of bioremediation aimed at breaking down per- and polyfluoroalkyl substances (PFAS) in soil and water. In 2023, BioCellection announced a new wastewater treatment technology that uses bacteria to remove up to 95% of nitrogen and phosphorus. Its potential is obvious, since nitrogen and phosphorus are the main pollutants of wastewater and can contribute to eutrophication – a condition in which excess nutrients in water bodies lead to algae blooms and fish kills.

In Russia, the biotech waste recycling industry is at an early stage of its development. The research carried out by the Russian Federal State Statistics Service (ROSSTAT) shows that in the agricultural and forestry sectors, up to 85% of waste is processed and rendered harmless, while alternative estimates indicate a significantly lower level (only 30%). It should be noted that the agro-industrial sector is one of the main waste producers, while current waste disposal standards, especially those related to livestock waste, are often ignored here.

The increased competition and intensification of the agricultural sector stimulate the use of innovative biotechnologies for the processing of agro-industrial waste. such as meals and pressings obtained as a result of oil extraction from sunflower seeds, soybeans, pumpkin, flax and other oilseeds, in order to transform them into nutritional supplements for feeding livestock. In this way, optimal utilization of almost all plant waste is achieved. In some farms, by-products of livestock activities are effectively converted into biogas.

Competition in agriculture stimulates the use of innovative biotechnologies in the processing of agro-industrial waste. Developed inexpensive methods allow the transformation of waste (such as meals and pressings obtained as a result of oil extraction from sunflower seeds, soybeans, pumpkin, flax and other oilseeds) into nutritional supplements for feed. In turn, livestock waste can be successfully used to produce fertilizers and biogas.

In Russia, bioremediation technologies (a set of methods for cleaning water, soil and the atmosphere using the metabolic potential of biological objects – microorganisms, plants, fungi, insects, worms and other organisms) are primarily used to clean contaminated areas from oil and oil products. According to expert estimates, 3 to 7% of the total volume of oil produced is lost in oil fields. Every year in Russia there are about 25-40 thousand accidents related to oil and oil product spills, and the total area of territory contaminated in this way in Western Siberia alone exceeds 800 thousand hectares. Several dozen preparations developed in Russia and the former Soviet republics are used for bioremediation of water bodies and soils contaminated with oil and oil products. However, the sales volume of biodestructor preparations is extremely small - no more than two million dollars [2].

Biotechnological methods will be increasingly used to purify polluted wastewater, to process waste from various industries, including the processing of rubber products, chemical substances, building materials, as well as materials containing radioactive elements, household waste, glass, plastics, and many others. The introduction of eco-biotechnologies in the industrial and socio-economic spheres is very relevant today, since the ecological recovery of the biosphere is considered a top priority, given the aggravation of problems arising as a result of the negative impact of human activity on nature.

The emergence of new materials and industries requires the development and improvement of classical methods of eco-biotechnology using innovative solutions (enzymes, sorbents, nanoparticles, biofuels, biofertilizers, biodegradable plastics).

The review presents a large volume of scientific publications aimed at finding new biological objects and developing new methods of eco-biotechnology, which indicates the demand for biotechnological approaches to solving the problems of anthropogenic waste disposal and restoring polluted environments. The purpose of this review is to analyze and summarize modern methods and approaches used to clean soil, water and air from various pollutants, as well as to characterize the main directions of development of modern environmental biotechnology.

1. Soil and soil ground cleaning from various pollutants

Mechanical, thermal, physical, chemical and biological methods are used to rehabilitate contaminated areas. However, if the contamination level is less than 5%, physical, chemical and thermal cleaning methods are expensive, do not solve the problem of complete cleaning and can cause additional harm to the environment. Therefore, the use of environmentally friendly biological methods is an obvious alternative. It has been shown that bioremediation has enormous potential and competitive advantages, primarily due to environmental safety and low cost [3].

Temperature, salinity, pH, availability of metabolically active substrates and nutrients, humidity, and electron acceptors significantly affect the bioremediation process [4]. Mineral substances such as nitrogen, oxygen, sulfur, and phosphorus play an important role in the biodegradation of pollutants [5].

Phytoremediation is based on the integration of the metabolism of plants and soil microorganisms [6]. Phytoremediation is environmentally safe and cost-effective compared to traditional approaches to industrial waste disposal and pollution elimination; it allows plants to act as biological barriers that isolate and neutralize unwanted elements through a complex of metabolic and physical processes: phytoextraction (absorption and accumulation), phytodegradation (decomposition), phytostabilization (prevention of migration), as well as the transformation and evaporation of harmful components - phytotransformation and phytoevaporation, respectively.

Phytoremediation converts pollutants into less toxic and less persistent substances in the environment [7]. Bioavailability of pollutants, chemical and physical characteristics of the soil are the dominant factors determining the activity and efficiency of phytoremediation mechanisms, which affect the mobility and toxicity of pollutants in the environment [8,9]. In synergy with plant roots and shoots, rhizosphere microorganisms participate in the processes of uptake, exudation and filtration, thus expanding the surface for microbial colonization and enhancing the degradation of pollutants [10].

Currently, various modifications of bioremediation technology are used:

- *Bioventing,* an i*n situ* bioremediation technology in which indigenous destructor microorganisms are activated by blowing air (oxygen) into the soil thus minimizing emissions of volatile pollutants [11]
- *Vermiremediation* , a technology in which earthworms are used to degrade toxic pollutants in the soil [12], thus increasing oxidation processes, as well as promoting the microbial viability and aeration of contaminated areas.

- *Mycoremediation i*nvolves the use of fungi to degrade hazardous pollutants such as petroleum hydrocarbons into less toxic or non-toxic forms [13]. The production of enzymes such as peroxidases for the breakdown of cellulose and lignin is one of the main mechanisms that allows various fungi to degrade persistent pollutants [14].
- *Phycoremediation,* the use of various algae (*Chlamydomonas, Chlorella, Botryococcus, Phormidium*, and macrophytes) to transform, break down and remove pollutants (such as petroleum hydrocarbons, phenols, biphenyls, pesticides, and phenolic resins) from contaminated aquatic environments [15] at relatively low cost [16]. Mixotrophic algae combine the ability to fix carbon dioxide with high bioremediation efficiency [17]. Algae also synthesize oxygen and remove excess nutrients [18]. Heavy metals can be bound in the polyphosphate bodi*es* of algae, which helps detoxify aquatic ecosystems [19].
- *Nanobioremediation.* A distinctive feature of this method is the use of nanoparticles, including such their varieties as biosynthetic nanostructures, nanocomposites, as well as clusters and nanoelements developed and synthesized at the microscopic level [20]. These nanomaterials or particles formed by plants or microorganisms have a size from 1.0 to 100 nm [21]. The role of such nanoparticles is based on their ability to transform and detoxify toxins using enzymatic processes due to their unique qualities manifested at the biochemical, chemical and physical levels [22].
- *Trichoremediation* is based on the use of keratinolytic and keratinophilic microorganisms with the ability of cometabolic degradation of substrates [6].

1.1 Biotechnologies for soil cleaning from petroleum hydrocarbons and other organic pollutants.

Environmental pollution by oil and oil products is currently a global problem [23]. In terms of the harmful impact on ecosystems, oil products and oil are second only to radioactive pollution [24].

It is known that microorganisms more quickly decompose simpler, linear and saturated alkanes, while polyaromatic hydrocarbons (PAHs) are less susceptible to microbial destruction. A number of microorganisms have unique enzymatic systems that carry out reactions of dioxygenation, monooxygenation, dehydration, O– and N– dealkylation and sulfoxidation. Some microorganisms have enzymes that catalyze the decomposition of not only specific but also complex mixtures of hydrocarbons; other microorganisms have the ability to attack only certain linear hydrocarbon structures [4]. Thus, the interaction of microorganisms in the ecosystem leads to more efficient destruction of pollutants [25]. The age of contaminants has a significant impact on the biodegradation process, it can decrease the bioavailability of hydrocarbons [26].

A number of studies also note the possible negative impact of the concentration and composition of hydrocarbons on the processes of their biodegradation. In the work [5] inhibition of growth of microbial cultures by high concentrations of crude oil was demonstrated.

Most biopreparations for cleaning oil-contaminated areas are mixed microbial consortia that can suppress native microflora. Therefore, the importance of studying the metabolic pathways of microbial communities is obvious [27], especially since the methodology of using modern omix approaches is actively developing.

Phytoremediation of soil contaminated with petroleum hydrocarbons was successfully carried out using several plants together with organic waste and organic fertilizers added to enhance the biodegradation process [28,29].

Successful removal of petroleum hydrocarbons using trichoremediation (the use of keratin-containing substrates - feathers and hair) is facilitated by additional processes such as absorption and adsorption [30-32].

1.2 Biotechnologies for soil cleaning from inorganic compounds

Persistent inorganic pollutants occur in nature in various forms such as salts, oxides, sulphides or organometallic complexes.

Pollution by radioactive isotopes may be of natural origin, from erosion of parent rocks and volcanic activity, or may be a consequence of human actions.

Many elements play a key role in maintaining biological processes. Iron, copper, zinc, manganese, nickel, boron, selenium, and molybdenum are considered essential trace elements for the health of flora and fauna, as well as soil microorganisms. Together, these elements form biogeochemical cycles that are fundamental to ecosystems [33].

The content of metals in a given area depends on the location, geological rock-forming material, soil-forming processes and anthropogenic sources such as fertilizers, wastewater, industrial emissions, solid waste, road dust and atmospheric deposition [34-35].

Arsenic, cadmium, chromium, copper, mercury, lead, manganese, nickel and zinc have a toxic effect on living organisms even at low concentrations [36,37].

Metals can bind to or precipitate on the surface of microbial cells through interactions with proteins or cell-associated polysaccharides [38]. Such extracellular adsorption can reduce the bioavailability of metals to achieve the goal of microbial remediation. Metals can undergo biotransformation in microbial cells through oxidation-reduction reactions, methylation and demethylation [39], thus becoming less toxic. Microorganisms can also use cytoplasmic proteins to bind metals, which reduces their toxicity [40]. When metals bind to functional proteins and disrupt their function, some microorganisms can initiate parallel metabolic pathways where alternative proteins with catalytic nuclei operate that do not bind to the toxic ligand of the metal [41]. In addition, a number of microorganisms can effectively remove metals from cells or store them in vacuoles, thereby reducing metal toxicity [42]. Some microorganisms increase the expression of extracellular substances in response to metal exposure: these substances contain functional groups capable of binding metals [43].

Asbestos is a general term for a wide range of naturally occurring hydrated mineral silicate fibers belonging to the serpentine and amphibole groups of rock-forming minerals. Asbestos-containing materials are often found in existing or historical old buildings [44]. Asbestos mining and processing sites are potentially significant sources of soil contamination [45].

The question of asbestos biodegradation remains open. It is known that the thermophilic bacterium *Deferrisoma palaeochoriense* can be used to remove iron from asbestos minerals through anaerobic respiration [46], thereby reducing their toxic properties.

1.3. Prospects for the use of remediation (including microbial) for soil cleaning from military industry pollution

1.3.1 Environmental pollutants from military activities

Organic pollutants entering the soil as a result of military activities are usually divided into potentially toxic compounds (PTC), energy carriers (fuel, oils), chemical warfare agents (CWA) and military chemical compounds (MCC) namely smoke and combustible materials, tear gases, herbicides. Their concentration in the soil in military areas can be unacceptably high, which, along with high toxicity and persistence, can lead to the emergence of environmental risks [47,48]. Pollution by PTC (fuel, oils, lubricants, paints, solvents) is mainly the result of the activities at military bases.

Pesticides are often used as repellents in various types of military materials, such as wall geotextiles or camouflage netting [49]. The organohalogen compound transfluthrin is one of the PTC group compounds. This semi-volatile organic compound is found mainly in the gas phase of air and in very small proportions in the solid phase. Per- and polyfluoroalkyl compounds (PFAC), also belonging to PTC, are found in military fire training areas. They can have long chains in their structure, including perfluorohexane sulfonic acid, perfluorooctane sulfonic acid and perfluorononanoic acid, or short chains, including perfluorobutane sulfonic acid and perfluoroheptanoic acid [50]. PFAC are a group of synthetic chemicals that are chemically stable and persistent, accumulate in living organisms and are toxic at low concentrations. Due to their relatively high solubility, they easily enter groundwater and reach the subsoil layer [51].

Military activities (training and combat operations, production, destruction and disposal of PTC) are a source of soil contamination with organic substances, including explosives and propellants. Organic contaminants can be classified as nitroaromatics, e.g., trinitrotoluene (TNT) and nitroamines, e.g., hexogen (RDX) and octogen (HMX) which are secondary explosives (i.e., detonated by primary explosives) most commonly used in military activities [52]. DNT (2,4-dinitrotoluene), which can occur as an impurity in the production of TNT, is also considered a priority contaminant by the US Environmental Protection Agency, it has low solubility in water and is found in soils at military testing sites.

Another group of toxic substances are propellants – chemicals used to produce energy or gas under pressure, which are then used to create liquid movement or propel projectiles. They are formed from one or more explosives mixed with various additives, where the main component is nitrocellulose. Other solid propellants used in firearms and artillery are nitroglycerin, nitroguanidine and dinitrotoluenes. Unlike TNT, RDX and HMX, nitroglycerin is rarely found in soils, and studies on this compound in soils are few. All of the above substances are not sorbed in soil and do not volatilize, which leads to their migration in the biosphere [52-54].

CWAs are highly toxic compounds used to kill, seriously injure, or incapacitate people. The main CWAs are nerve agents and vesicants. There are two subgroups of nerve agents: G-agents (derivatives of organophosphorus esters of phosphorus) and V-agents (which have the same chemical composition as G-agents but also contain sulfur). V-agents have low volatility, spread more slowly, and are therefore more persistent in the environment [55]. The hydrolysis is often considered the main pathway involved in the environmental fate of CWAs. Intermediate hydrolysis products can be more persistent and more toxic [56,57].

1.3.2. Nature protection technologies applicable for reclamation of contaminated military facilities

Existing methods of soil remediation can be applied both *in situ* and *ex situ*, and may include various biological, physicochemical and thermal processes. Biotechnological methods are usually cheaper compared to other methods of cleaning, and the soil retains therewith many of its key functions [58].

Organophosphorus compounds (including PFAC) have strong C≡F bonds in their structure, so they are almost not subject to biodegradation [51], but can be taken up by plants through phytoremediation [59,60]. Organophosphorus-degrading enzymes have been studied for their ability to degrade nerve agents such as tabun [61] and sarin [62]. The biodegradation of sulfur mustard by microorganisms is becoming increasingly feasible, although further developments are needed to improve the solubilization of aged forms of this agent in contaminated soils to facilitate its microbial transformation into harmless products [63]. It was shown that haloalkane dehalogenase DhaA on the surface of *Bacillus subtilis* spores was able to degrade sulfur mustard [64]. The possible involvement of microorganisms in the release of soluble arsenic compounds from arsenic agents was also reported [65]. In 2013, Lorenz and co-authors [66] investigated the ability of *Pseudomonas fluorescen*s, engineered to express cytochrome P450 XplA, to degrade RDX in the rhizosphere.

Various soil amendments, such as organic waste, can be added to the soil to stimulate microbial activity. Composting can also be used in the bioremediation of sites contaminated by military activities.

The degradation of military energy substances in contaminated soil during bioremediation was also studied to determine suitable conditions for their biodegradation [67,68]. It turned out [67] that an increase in the activity of anaerobic microorganisms is closely related to the disappearance of RDX from soil upon the introduction of by-product glycerol (a waste product of biodiesel production) on the territory of a former military testing ground. A sulfate-reducing consortium was used to remove TNT from the soil [69]. In another study, the degradation rate of RDX was determined after the introduction of a bioadditive, the *Gordonia* sp. KTR9 strain, to assess the effectiveness of biostimulation in a RDX-contaminated aquifer at a former military facility [70].

Phytoremediation is a favorable method for the removal of hydrophilic organic compounds [71]. Plants such as barnyard grass (*Echinochloa crus galli*), annual sunflower (*Helianthus ann*uus), theophrastus's balsam (*Abutilon avicennae*), vetiver (*Vetiveria zizanioides*) [72] and southern reed (*Phragmites australis*) for TNT [69]; guinea grass (*Panicum maximum*) for RDX and HMX [73,74] were used for phytoremediation of explosives. Some transgenic plants expressed nitroreductase and showed a significant increase in the ability to absorb and detoxify TNT [75]. Rylott and co-authors [76] developed TNT-resistant *Arabidopsis* plants for the biodegradation of RDX. Switchgrass (*Panicum virgatu*m) was used to destroy RDX in soil [77]. Sycamore maple (*Acer pseudoplatanus)* is another plant that was evaluated for phytoremediation of soils contaminated with explosives [78].

Results from a laboratory experiment showed effective removal of diphenylarsinic acid, a hydrolytic or oxidative organic product of toxic agents, and restoration of ecological functions of the soil using the fern ribbon (*Pteris vittata*) and the symbiotic bacterium *Phyllobacterium myrsinacearum* [79]. In a field study at the fire training ground at Stockholm-Arlanda Airport (Sweden), mixed plantings of silver birch and Norway spruce [59,60] showed good results in cleaning the soil from PFAC.

1.4. Soil and soil ground cleaning from pesticide pollution

The use of pesticides is associated with the growth of global demand for food products and food security issues [80]. Over the past 30 years, the use of pesticides per 1 ha of soil has increased almost 2-fold [81].

Pesticides, along with PAHs and heavy metals, are common environmental pollutants, they have high biological stability and pose a serious danger to human and animal health [80,82,83]. Pesticides can not only cause neurotoxicity, cancer, but also lead to death [84-86].

Complete removal of pesticides from soils and grounds is a rather labor-intensive task, since physical and chemical methods of remediation provoke the appearance of secondary pollutants and are expensive [87]. Therefore, the development and application of biological methods for cleaning soils contaminated with pesticides are very relevant.

1.4.1 Soil bioremediation with microorganisms

Microorganisms can totally degrader or partly transform pesticides into non-toxic metabolites [88,89]. Bacteria of the genera P*seudomonas, Bacillus, Actinobacter, Acinetobacter, Burkholderia, Klebsiella, Ochrobactrum, Rhodococcus, Stenotrophomonas, Sphingomonas, Novosphingobium, Streptomyces and Achromobacter* are known for their ability to destroy pesticides both in consortia and when used individually [90-93]. Among fungi, this ability was reported for *Phanerochaete, Penicillium, Aspergillus, Ganoderma, Trametes versicolor, Cunninghamella*, etc. [94-98]. Microalgae and cyanobacteria can use pesticides as the only source of carbon [99-101]. The ability to photoautotrophy and nitrogen fixation gives them an advantage over other microorganisms. The ability to oxidize various organochlorine and organophosphorus pesticides was found in the microalgae *Spirulina, Anabaena, Arthrospira, Nostoc, Phormidium,* etc. [102]. Currently, not only consortia based on a single group of microorganisms (bacteria, microalgae, or fungi) are used, but also those consisting of mixed groups [101,103].

An organophosphorus hydrolase OpdA was isolated from *Agrobacterium radiobacter*, which is one of the most effective enzymes degrading organophosphorus compounds [104]. OpdA was later successfully field tested [105] as a commercial product LandGuard^{TM} by the Australian company Orica Watercare [106].

When cultivating the *Pseudomonas* sp. S2 strain in a bioreactor, extracellular laccase S2LAC was obtained, capable of degrading organophosphorus pesticides (dichlorvos, chlorpyrifos, monocrotophos and profenovos) [107]. Another extracellular laccase from the fungus *Trametes versicolor* in combination with various mediators showed a degradative activity against isoproturon, procymedone metabolites, and glyphosate [108-110].

An important factor influencing the degradation of a pesticide in natural conditions is its molecular structure. The addition of certain groups/side chains to the pesticide molecule can both enhance the ring cleavage mechanism and make the substrate more resistant to biodegradation [111].

To stimulate bioremediation, it is possible to add nitrogen, phosphorus, microelements, secondary carbon sources and other compounds to the contaminated area, and and change the soil pH . An increase in the consumption of DDT (l,l,l-trichloro-2,2-bis (p-chlorophenyl) ethane) and its main metabolites from 23%

in the control (without cosubstrate) to 67% with the addition of trace amounts of phenol, hexane or toluene was reported [112]. Addition of lactate and/or anthraquinone-2,6-disulfonate as electron donors accelerated the pentachlorophenol (PCP) transformation in iron-rich soils. Electrochemical studies confirmed the high reduction potential and large number of electrons generated under biostimulation conditions, which were responsible for the higher rates of PCP transformation; an increase in the number of dechlorinating and iron-reducing bacteria was shown [113].

One way to increase the bioavailability of pesticides and accelerate their bioremediation is the use of biosurfactants and biosurfactant-producing microorganisms [114,115]. Biosurfactants reduce the surface area and interfacial tension of immiscible liquids and increase the solubility and sorption of hydrophobic pesticides.

Bioaugmentation was used in the treatment of rice fields contaminated with the thiocarbamate pesticide molinate with the bacterial culture *Gulosibacter molinativorax* [116]; the structure of the soil bacterial community was unaffected therewith. Bioaugmentation of soils contaminated with fenpropathrin using the strain *Bacillus* sp. DG–02 significantly increased the rate of this insecticide disappearance and reduced its half-life in soils [117]. Inoculation of soil contaminated with the herbicide 2,4-dichlorophenoxyacetic acid (200 mg/kg) with the strain *Novosphingobium* sp. DY4 for 3–4 and 5–7 days led to a decrease in the concentration of this pollutant by 50% and 95%, respectively [118]. No significant changes in the structure of the microbial community were observed.

At a concentration of 300 mg/kg soil, the fungal strain *Aspergillus terreus* JAS1 completely degraded chlorpyrifos and its main metabolite 3,5,6-trichloro-2-pyridinol in 24 and 48 hours, respectively [119]. In some cases, bioaugmentation is used in combination with biostimulation. Thus, when cleaning soil contaminated with the herbicide atrazine, the soil was inoculated with the strain *Pseudomonas* sp. ADP, and citrate and succinate were added for biostimulation [120]. Strains *Aspergillus oryzae* and *Trichoderma longibrachiatum* enhanced the degradation of endosulfan and imidocloprid (up to 99%) in soils enriched with manure [121,122].

1.4.2. Phytoremediation

This approach combines the use of plants and their associated microorganisms for soil remediation. Pesticides are taken up by plants from the soil via cell membranes [123] and can be subject to evapotranspiration, phytodegradation, phytoextraction or rhizodegradation [124]. A successful translocation and bioaccumulation of DDT and its metabolites by the pumpkin *Cucurbita pepo* is explained by the high transpiration volume, big aboveground biomass and composition of root exudates [125]. Tomatoes are another candidate for soil remediation from DDT [126]. Sunflower has the highest capacity for phytoextraction of the organochlorine pesticide endosulfan compared to tomatoes, soybeans or alfalfa [127]. A good choice may be plant species that naturally grow in pesticide-contaminated areas or that are able to grow on specific contaminated soil.

The rate of accumulation of organochlorine pesticides is a specific characteristic of plant species and depends on the degree of soil pollution [128]. The ability to accumulate organochlorine pesticides was demonstrated using endosulfan and two cereal plants – vetiver (*Vetiveria zizanioide*s) and foxglove (*Digitaria longiflora*) [129].

Rhizoremediation was demonstrated using the example of the stimulating effect of the winter wheat rhizosphere on the pentachlorophenol-degrading strain *Sphingomonas chlorophenolic*a [130], as well as in the detoxification of cypermethrin-contaminated soils by the herbaceous perennial plant *Pennisetum pedicellatum* [131].

1.4.3 Vermiremediation

The studies of the soil microcosms showed that the addition of earthworms resulted in the formation of non-extractable atrazine residues, a deeper and more heterogeneous distribution of atrazine in the soil, and promoted the sorption of atrazine, which in turn increased the stability of atrazine [132]. Earthworms (*Lumbricus terrestris* and *Aporrectodea caliginosa*) significantly affected the structure of bacterial communities in atrazine-contaminated soils and reduced the abundance of the inoculated population of *Pseudomonas* sp. ADP, a strain that degrades atrazine [133]. However, there are examples in the literature of the positive effect of earthworms on the purification of soils from pentachlorophenol due to an increase in microbial biomass and its activity [134-136].

2. Water Environment Cleaning

2.1 Wastewater cleaning

Any activity using water, domestic, agricultural or industrial, results in the formation of wastewater contaminated with various chemicals that may be toxic [137,138].

For primary wastewater treatment, mechanical, physical, physicochemical, and chemical methods are used [137]. Before discharge into the environment or before reuse, pre-treated wastewater must undergo secondary treatment using the most appropriate biological, physical or chemical methods. Secondary treatment removes most of the residual pollutants present in the wastewater, although some dissolved nutrients such as nitrogen and phosphorus may remain.

Pollution sources are usually divided into point and non-point. Point sources include municipal and industrial wastewater discharges, while agriculture (considered as surface return flow from irrigation), rain water and other runoffs are non-point sources. Domestic wastewater contains decaying food, detergents, excreta, and pathogens. Wastewater from chemical and pharmaceutical industries usually contains hazardous substances that must be inactivated and disposed of. Agricultural wastewater containing organic matter, antibiotics, and pesticides also requires treatment and recycling.

Various biological processes are used to dispose of organic matter present in wastewater, such as detergents, human waste, oils, and food products. Microorganisms are able to process organic matter contained in wastewater. Usually, three categories of biological treatment processes are distinguished: aerobic, anaerobic, and composting. Depending on the nature of growth or structural organization of the microbial community, biological processes are divided into two groups: growth in a suspended state (suspension), when microbial cells grow in a plankton form in a large volume of liquid medium, and growth in an attached state in the form of biofilms [138].

Recent advances in municipal and industrial wastewater treatment technologies include several innovative approaches aimed at improving efficiency and environmental sustainability [139].

1. Membrane bioreactors combine biological treatment with membrane filtration, which allows for efficient solid-liquid separation and pathogen removal. Membrane bioreactors produce high-quality wastewater suitable for reuse.
2. Advanced oxidation processes use powerful oxidizing agents (such as ozone or hydrogen peroxide) to break down organic contaminants in industrial wastewater, including difficult-to-treat substances. This technology is effective in removing toxic compounds and improving wastewater quality.
3. Engineered wetlands mimic wetland ecosystems to filter pollutants through biological and physical processes, providing a cost-effective solution for municipal wastewater.
4. Bioremediation is increasingly used in the treatment of refinery wastewater to remove hydrocarbons and heavy metals.
5. Electrocoagulation uses electrical currents to treat wastewater, effectively removing suspended solids and pollutants, making it suitable for both municipal and industrial applications.

These technologies not only improve treatment efficiency, but also contribute to the restoration of water resources and the achievement of sustainable development goals.

2.2. Cleaning of natural water bodies

Recent advances in the bioremediation of contaminated water bodies include the use of innovative microbial and plant-based methods and bioengineering approaches. A promising approach is the use of biochar, a carbon-rich material derived from organic waste that can improve water quality by adsorbing pollutants and providing a habitat for beneficial microbes [140]. A method for the biodegradation of persistent organic pollutants using microalgae has been estimated [141] to be a promising solution for water body treatment. Advances in metagenomics and synthetic biology allow for a better understanding of microbial communities and the tailoring of bioremediation strategies to specific pollution scenarios. Scientists are also exploring the use of nanotechnology to deliver nutrients and additives that enhance microbial activity in contaminated environments [142]. These developments have great potential for more efficient and sustainable methods of remediating contaminated aquatic ecosystems.

2.2.1 Cleaning and restoration of reservoirs

Compared with other technologies, surface water bioremediation methods are not invasive and do not disrupt the interconnections of the trophic pathways in aquatic ecosystems [143]. In most cases, microbiological bioremediation can quickly and effectively restore water quality in polluted and eutrophic reservoirs. Microorganisms in biopreparations are also successfully used for sludge mineralization. To maintain the effect of microbiological treatment, submerged and floating macrophytes are planted in reservoirs in so-called ecotones [144]. Microalgae are the initial link in the food chains of reservoirs, macrophytes produce oxygen, create favorable physicochemical conditions and econiches for the habitation of other aquatic organisms; they can serve as food for many animals living in reservoirs. Plants growing along the banks of reservoirs strengthen the shoreline, prevent the stirring up of bottom sediments, thereby reducing water turbidity and ensuring the flow of sunlight [144].

One of the first studies of a eutrophic reservoir, providing an idea of the effectiveness of using effective microorganisms (*Lactobacillus, Bifidobacterium, Pediococcus, Lactococcus, Streptococcus, Rhodopseudomonas, Aspergillus, Mucor, Streptomyces*) in improving water quality (by reducing the number of heterotrophic bacteria, coliform bacteria, enterococci, *Salmonella* spp.), is known for the Turawa reservoir on the Mala Paniew River in Poland (2019–2021). The use of ProBio series biopreparations improved the trophic status of the reservoir by ~8% [145].

An interesting approach to regulating the trophic chain “fish – bivalves – phytoplankton – microorganisms” through controlled fishing was proposed by Chinese researchers [146] and successfully applied in the Xiaoxianshan and Shiqishan reservoirs on the Yangtze River.

2.2.2 Restoration of polluted river water

River pollution can be a source of waterborne diseases, as well as cause odors and air pollution [147].

Waste sources include industrial production, wastewater, landfills, commercial markets, restaurants, and agriculture. Agrochemicals (fertilizers, pesticides, herbicides, etc.) pollute rivers with various chemicals, including nitrates and phosphates. Rain water runoffs also bring treated and untreated wastewater, industrial waste, petroleum products, hydrochemicals, and road dust into river water.

Polluted river water can be remediated either by the i*n situ* water treatment or by the pollution control at the source of contaminants. There is no universally effective method for cleaning river water from different types of pollutants. Therefore, complex technologies and hybrid methods are required to restore the purity of river water. Several biological and ecological treatment technologies were described, among them microbial bioremediation, biofilm technology, contact oxidation, membrane bioreactor technology, ecological ponds, plant-based treatment, ecological floating mats and artificial wetlands.

In situ approaches primarily use the metabolic activity of plants and microorganisms to absorb, accumulate, or degrade pollutants in water. Aeration can increase the diversity and abundance of microbial communities that degrade organic compounds in river water. Riverside protection using gabions, aquatic and soil macrophyte plants can improve riparian biodiversity and ecosystem restoration.

Aquatic plants, including microalgae and macrophytes, show high potential for river water purification. Planting pollutant-tolerant plants on the banks can help purify river water by absorbing, adsorbing, storing and degrading pollutants either at the riverbank or at the point of wastewater/rain water discharge [147].

Osadebe A.U. et al. [142] investigated the removal of oil products from river water using composites based on iron oxide nanoparticles applied to biochar with immobilized degrading bacteria and monoammonium phosphate at a pollution level of 10% v/v. Treatment with a complex of the listed components stimulated the most complete and rapid removal of hydrocarbons compared to the use of individual components.

2.2.3 Restoration of artificially created wetland system

Artificial wetlands (AWLs) consisting of sediment-rooted plants combine physical and biogeochemical processes to effectively remove water pollutants and restore the natural river ecosystem, they have low operating costs, are easy to maintain, do not generate secondary pollution, provide economic and environmental benefits, and are highly effective. However, they require a large area, have a low hydraulic load, and are unstable to high pollutant input rates; seasonal plant mortality and diseases also affect the effectiveness of AWLs [148].

Floating wastewater treatment beds, natural or artificial, combine the properties of natural ponds and hydroponic vegetation. The plant roots submerged in water not only act as a natural filter to remove pollutants but also provide surface area for enhanced microbial growth and biofilm formation. Endophytic organisms localized in the root systems in floating mats make a significant contribution to the control of aquatic pollutants. Decomposition, adsorption, denitrification, root trapping and sedimentation, as well as assimilation are key processes involved in the removal of pathogens, organic matter, toxic metals, and organic compounds from water [149-151].

The use of AWLs has some limitations due to the clogging of the filter layer of the substrate and the need of a large coverage area. In contrast, ecological floating mats are becoming popular for river water treatment due to their cost-effectiveness, quite a high efficiency of pollution removal and mobility. They can provide habitats for birds and fish, inhibit the growth of phytoplankton and protect the riversides from erosion.

The potential for purification of river water was assessed using a hydroponic system based on floating beds with water spinach (*Ipomoea aquatica*) and glutinous rice plants (*Semnostachya menglaensis*): the concentration of total nitrogen and phosphorus in the water was significantly reduced [152], transparency increased, and the quality of the river water improved. A floating bed was described [153] that was based on foamed polyethylene for cultivating various plants capable of removing pollutants from river water. The combination of the Indian canna (*Canna indica L.*) plant with a floating substrate effectively purified the water from biogenic substances [154].

The use of complex engineering systems (structures for separating algae biomass, floating mats with flowering plants on the surface, submerged platforms with underwater plants and bottom coatings with microorganisms) demonstrated effective removal of biogenic substances and heavy metals and the increased water transparency [155].

A combination of cattail (*Typha domingensis*) and brown clematis (*Clematis fusca*) with endophytes penetrating their roots provides excellent purification of river water from domestic and industrial wastewater, while significantly reducing both chemical oxygen demand (COD) and biological oxygen demand (BOD) by 87% in four days [156].

The alga *Elodea nuttallii* is capable of separating nitrate and ammonium nitrogen into fractions, which are then either deposited in bottom sediments or absorbed by the plant itself [157,153]; in this case, the ammonium form of nitrogen is more actively absorbed. Such selectivity prevents algal "blooms" of water.

Factors affecting the performance of floating beds. These floating ecosystems are not affected by changes in water levels, waves, and floods. However, effective purification of river water using floating beds depends on many parameters, primarily on the selection of appropriate plants. *Canna indica* surpasses such species as sweet flag (*Acorus calamus*) and other aquatic organisms in its purification capabilities [158].

The performance of such systems depends on microorganisms living in symbiosis with plants: α- and β-proteobacteria [159]. Temperature, seasonal changes, duration of contact of contaminated water with the floating system and concentration of impurities are also important for the functioning of these bioremediation systems [160].

Restoring of river ecosystems with aquatic animals. Fauna is an indispensable tool for improving the quality of water resources. For example, shellfish, silver carps and carps filter out pollutants, thus reducing the amount of organic matter and algae. Sometimes the efficiency of filter fish, as in the case of silver carp, is low due to the toxicity of algae and anthropogenic pollutants.

Application of microbial agents for purification of water systems. The use of microorganisms for purification of polluted water bodies can increase the level of dissolved oxygen up to 5.0 mg/l [161] and moderately remove ammonia nitrogen (NH_3–N). They can reduce COD and total phosphorus content, and significantly improve the color of river water. Microbial technologies are simple and potentially stable in long-term use. The use of nitrobacteria together with other microorganisms and humic acids is effective for the removal of total nitrogen and phosphorus, ammonia nitrogen (NH_4–N), it reduces COD and turbidity of water in polluted water bodies [162-164].

The combination of specific microbial agents with photosynthetic bacteria and microalgae-bacteria systems stimulates active decomposition of organic components and reduces COD and BOD values by approximately 70%. Aeration and the use of various carriers, including water beds, also contribute to the disinfection of water resources.

Biofilm reactors. Recently, significant progress has been made in the application of biofilm reactors using biomembranes directly attached to various substrates including river bottoms. Aeration ensures the elimination of organic and inorganic contaminants due to adsorption, destruction, and filtration The stability of the structure and the cleaning capacity of biofilms directly correlate with such parameters as hydraulic load, water flow rate, temperature conditions and the choice of materials for biomembranes [165].

Wang and co-authors [166] developed a technology that combines the use of aerators, biofilms and specialized bacteria to reduce COD, BOD, total nitrogen, total phosphorus, and solids in river water. Several other technologies were developed for the same purpose and also for the improvement of the clarity of contaminated water. These technologies are based on the use of bioceramic carriers [167], biological filter media, pebble-zeolite composite pack for biofilm formation, biocord (substrate for microorganisms) and recirculating sand filter [158]. The use of filamentous bamboo as a biofilm carrier demonstrated a significant potential for the treatment of contaminated river water [168].

3. Air purification

3.1 Air purification in residential premises

The main pollutants of urban air include various gases (e.g. carbon dioxide, sulfur dioxide, nitrogen oxide and dioxide), heavy metals, PAHs, and solid particulate matter (PM) (e.g. PM2.5, PM10) [169,170]. The latter are a complex mixture of abiotic and biotic particles (microorganisms and microparticles of biological origin) [171]. Solid particles can cause respiratory, cardiovascular, and oncological diseases [172,173].

Increasing urbanization has resulted in city dwellers spending up to 90% of their time indoors [174], making indoor environmental quality a global public health issue [175]. Indoor air pollution levels can be higher than outdoors because indoor air is additionally polluted by volatile organic compounds (from furniture, paints, solvents, and finishing materials), carbon dioxide (from human respiration and gas combustion), and particulate matter of varying sizes [176,177].

The development of biotechnological systems to improve indoor air quality was initiated by space exploration [178]. Plants were expected to remove pollutants (volatile organic compounds – VOCs) either by uptake through stomata or by absorption and adsorption on the plant surface [179-180]. The potential of epiphytic, endophytic and rhizosphere microbiota in VOC removal was identified [181-183]. The most studied is the so-called passive biofiltration – the use of potted indoor plants to purify indoor air [184]. Compared to irrigated biofilters, it is cost effective and does not require complex engineering solutions [185]. The specific plant species to be used depends on the type of pollutant [186]. *Chlorophytum comosum* is one of the most widely used plant species [187]. For nitrogen dioxide removal, peace lily (*Spathiphyllum wallisii* '"Verdi"), fragrant dracaena (*Dracaena fragrans* "Golden Coast") and zamioculcas (*Zamioculcas zamiifoli)* are known to be quite efficient [188]. "Green walls" (biowalls) with different plant species can remove a mixture of different pollutants with less space requirements [189].

Activated carbon is used as a hydroponic substrate for indoor plants [190]. Xu and co-authors [191] grew *Chlorophytum comosum* in a column with inert substrates and compost to remove high concentrations of formaldehyde.

Microalgae, which can be grown in bioreactors, are used to remove pollutants, including CO_2 from indoor air [192]. A technology was developed for cleaning air from ultrafine particulate matter (PM2.5) using *Chlorella pyrenoidosa* immobilized on cotton fabric [193]. This technique increases the cell density, thus reducing the volume of the biofilter, and simplifies the process of the biofilm replacement.

3.2. Prospects for the use of microorganisms to reduce the volume of gas emissions from industrial and power plants

Air pollution causes acidification of water masses, eutrophication of water bodies and appearance of smog, which damage natural ecosystems, human health and lead to economic losses. Thus, the ongoing tightening of air emission standards is natural and will continue to occur [194].

WHO has presented a list of six pollutants that are known as typical air pollutants in industrialized countries: nitrogen oxides (NOx), sulfur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2) and suspended particulate matter [195]. In addition to the so-called "flue gases" (CO, CO_2, SO_X, NO_X), the main air pollutants in industrial production are hydrocarbon combustion products, inorganic chlorine and the hydrocarbons themselves. Large amounts of volatile organic compounds, benzopyrene, are emitted during asphalt production [196]. The processes and technologies currently used for cleaning flue gases are energy-intensive, quite expensive and environmentally unsafe.

Currently, developed economies are experiencing significant declines in total emissions of NOx, PM2.5, SOx and CO. On the other hand, low- and middle-income countries are experiencing exponential growth in emissions, especially those in the process of accelerating industrialization, such as China, India and other Southeast Asian countries [194].

Microorganisms used for cleaning gas emissions require the provision of necessary nutrients dissolved in water. Such a nutrient medium is first used to irrigate the gas flow. It is also necessary to provide for the regeneration of the water used and its return to the cycle of cleaning air emissions, as well as to take into account the need to remove excess biomass that forms biofilms.

As is known, microorganisms are capable of living and actively utilizing pollutants in a fairly narrow range of relatively low temperatures: from 20° to 70-100°C; for a specific microorganism, this range narrows to Δ20°C, and sometimes even less. Thus, there is an obvious need for cooling flue gases that have a high temperature, and thermoregulation of pollutant neutralization units - biofilters - to avoid the death of microorganisms.

When creating biofiltration systems for gas emissions, it is necessary to use irrigation to dissolve the gas or gas mixture in water so that microorganisms have the opportunity to biochemically transform them. The gas flow containing the pollutants contacts the aqueous phase; the pollutant is absorbed and destroyed by microorganisms [197]. Multi-stage purification of air emissions containing a multi-component mixture, such as phenol and formaldehyde, is possible by passing the gas successively through absorbent solutions containing various microbial cultures [198].

A conventional biofilter can be successfully used for the utilization of inorganic compounds such as hydrogen sulfide [199], ammonia [200], as well as organic compounds: amines [201], methyl sulfides [199, 201], mercaptans [201], carbon disulfide [199], ketones and chloroform [201], aromatic compounds of the BTEX group (benzene, toluene, ethylbenzene, xylenes) [199, 201], aldehydes [202], including mixtures of volatile organic compounds, etc. [203].

Trickling biofilters were developed to carry out the microbial degradation of carbon disulfide and hydrogen sulfide [204], vinyl chloride [205], methyl sulfides [199], carbon tetrachloride [205], volatile organic compounds (chlorine-containing compounds) [204], styrene [206], hydrocarbons of the BTEX group [205, 207], and some other compounds [208].

In order to increase the absorption of gas and pollutant particles in the cleaning liquid, a number of authors propose a method that includes stages of contact of the polluted gas flow in countercurrent with a jet containing microorganisms [198,209].

In the chemical industry, changes in the concentration of pollutants and the composition of exhaust air make biofiltration a complex technology. As a possible solution, a coordinated scheme was developed and implemented that includes a cyclic two-process (adsorption/desorption) unit and a jet recirculation air biofilter [210].

Microalgae technology [211] allows for the production of microalgae biomass up to 742 mg per L^{-1}, the capture of up to 80% of CO_2, and the decomposition of volatile aromatic compounds.

Nazarova and co-authors [212] identified the sources of volatile aromatic compounds in confectionery production that make the greatest contribution to air pollution with terpenes and benzaldehyde; microbial strains capable of transforming the detected aromatic compounds in the process of biotechnological air purification were selected. The design and technological features of biotechnological installations for cleaning the gas-air mixture were reported.

An integrated "biomass-solar-natural gas" hybrid model using algae was developed and analyzed for its technical and economic feasibility as an approach to reduce carbon emissions and utilize solar energy to produce electricity and heat from biogas. It was shown that the productivity and amount of algae biomass correspond in thermal equivalent to the biogas requirement for a crude oil heating system, i.e. the hybrid model is technically viable [213].

4. Microplastics as an environmental pollutant

In the modern world, the production and use of synthetic plastic-based materials is constantly growing due to their strength, low cost and lightness. Very little of these materials are recycled or incinerated – about 20% [214]. In the environment, most discarded plastic degrades into small particles less than 5 mm in diameter – microplastics (MP). MP constitutes the dominant part (about 90%) of all plastic waste [215], with the main compounds being polystyrene, polypropylene and polyethylene.

MP poses a pressing environmental threat, negatively impacting both aquatic (rivers, lakes, seas, oceans, etc.) and terrestrial ecosystems [216]. A wide range of fauna, when consuming MP, suffer from a false sense of satiety, pathological stress, decreased growth rate and reproductive disorders [216,217]. In view of the inhibitory effect of MP on various life forms and systems, the search for approaches and methods to reduce the amount of MP has become a priority [218]. MPs are passively enriched with various chemical impurities, adsorb metals and persistent organic pollutants, thereby forming harmful conglomerates. It was noted that such conglomerates increase the problems of environmental pollution, especially in terms of soil fertility and the state of water systems [219,220]; the biogeochemical balance in natural ecosystems is on the verge of collapse.

In recent years, many studies have been conducted on the distribution, fate, behavior, quantity, and impact of MPs [221]. Although MPs can persist in the environment for a long time, they can be degraded by some microorganisms [222, 223]. Thus, strains of micromycetes *Penicillium* spp. demonstrate a high degree of degradation of polymeric materials [224].

The use of microorganisms will enhance the biodegradation of MPs without harming the environment [225-227]. In natural environments, MP degradation is a complex process that combines physicochemical and microbiological factors [228]. To date, few active MP-degrading strains have been isolated.There is a clear lack of knowledge regarding the interactions between microorganisms and MPs and MP removal [229]. It should be noted that at present, most of the work has been carried out in laboratory conditions, and the emergence of commercial biotechnologies for MP utilization is possible only in the future.

Conclusion

The application of bioremediation technologies aimed at detoxifying pollutants in soil, water and air environments is at the core of environmental biotechnology. Microorganisms and enzymes used in bioremediation processes help transform toxic elements into harmless compounds. Bioremediation is an environmentally responsible and sustainable method for eliminating pollution caused by industrial accidents, waste and other anthropogenic activities. Due to this, bioremediation is increasingly gaining recognition in government agencies and corporations as an effective means of cleaning up ecosystems, which contributes to its dissemination and growth of the market segment.

It is expected that as the goals of sustainable development are achieved and the “ecological footprint” is reduced, the demand for “green” biotechnologies will only increase. The continued focus on the development of highly effective methods for water, soil and air purification opens significant prospects for scaling up the application of ecobiotechnological strategies in the foreseeable future.

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