Selected pollutants of the aquatic environment – challenges, health hazards, and removal methods

Wybrane zanieczyszczenia środowiska wodnego – wyzwania, zagrożenia zdrowotne i metody usuwania

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The current challenge for environmental protection is pollution from the group of emerging pollutants (ECs). Emerging contaminants are a group of highly toxic substances present in the environment at very low concentrations. These contaminants often enter aquatic ecosystems from various sources, such as pharmaceuticals, cosmetics, and industrial chemicals. Due to their bioaccumulative properties, ECs can move through the food chain, eventually reaching human bodies. Due to their bioaccumulative properties, ECs can move through the trophic chain, eventually reaching the human body. The aim of the article was to indicate the need for further research on the toxicity of these pollutants, their impact on the environment and human health, and to develop guidelines regulating their permissible concentrations. The importance of developing effective methods for removing ECs from various environmental components was also pointed out. Implementing these removal techniques, alongside regulations limiting the use of these substances, is essential to protect water quality and public health.
Keywords: pollutants, pollution removal, public health, environmental protection

Aktualnym wyzwaniem dla ochrony środowiska są zanieczyszczenia z grupy nowo pojawiających się zanieczyszczeń (ECs). Nowopojawiające się zanieczyszczenia to grupa silnie toksycznych substancji obecnych w środowisku w bardzo niskich stężeniach. Te zanieczyszczenia często przedostają się do ekosystemów wodnych z różnych źródeł, takich jak produkty farmaceutyczne, kosmetyki i chemikalia przemysłowe. Ze względu na właściwości bioakumulacyjne, ECs mogą przemieszczać się przez łańcuch troficzny, ostatecznie docierając do organizmu człowieka. Ich trwałość sprawia, że pozostają w środowisku przez wiele lat, co prowadzi do szkodliwych skutków dla różnych elementów ekosystemu oraz zdrowia ludzi. Celem artykułu było wskazanie potrzeb dalszych badań nad toksycznością tych zanieczyszczeń, ich wpływem na środowisko i zdrowie ludzi oraz opracowania wytycznych regulujących ich dopuszczalne stężenia. Wskazano również znaczenie opracowania skutecznych metod usuwania ECs z różnych komponentów środowiska. Wdrożenie technik usuwania tych zanieczyszczeń oraz przepisów ograniczających ich stosowanie, jest niezbędne do ochrony jakości wody i zdrowia publicznego.
Słowa kluczowe: zanieczyszczenia, usuwanie zanieczyszczeń, zdrowie publiczne, ochrona środowiska

Introduction

One of the key contemporary challenges is ensuring the quality and availability of water for consumption. Industrial development and increasing urbanization have introduced a variety of chemical compounds into the environment, including emerging contaminants (ECs). The water cycle plays a crucial role in the spread of these pollutants [1,2].

ECs are pollutants that have been widely studied only over the past two decades. They are commonly found in both aquatic and terrestrial environments. Examples of these contaminants include pesticides, plasticizers, pharmaceuticals, personal care products, their metabolites and transformation products, as well as antibiotic resistance genes. Most ECs have toxic effects on aquatic organisms and disrupt ecosystem balance. Some of these substances exhibit bioaccumulative properties, allowing them to move through the food chain and negatively impact human health, particularly the endocrine and immune systems. They are considered potentially carcinogenic and neurotoxic [3,4].

The primary sources of ECs transport to aquatic ecosystems include hospitals, where contaminants enter sewage systems and are subsequently directed to wastewater treatment plants (Figure 1). A second source involves industrial sites where ECs are generated as byproducts. Most of this wastewater is directed to sewage systems and processed at treatment facilities; however, in certain cases (e.g., stormwater overflows), some wastewater potentially containing ECs may flow directly into surface waters. Another pathway includes surface runoff, which can carry ECs into both surface and groundwater systems [1,5].

Unfortunately, current wastewater and water treatment technologies are not fully equipped to effectively remove emerging contaminants. Wastewater treatment processes were primarily designed to eliminate standard pollutants, such as biodegradable organic matter, suspended solids, nitrogen, and phosphorus. Similarly, drinking water treatment technologies also have limitations in removing emerging contaminants. Typical water treatment processes, such as coagulation, filtration, and disinfection, are primarily focused on removing particles and

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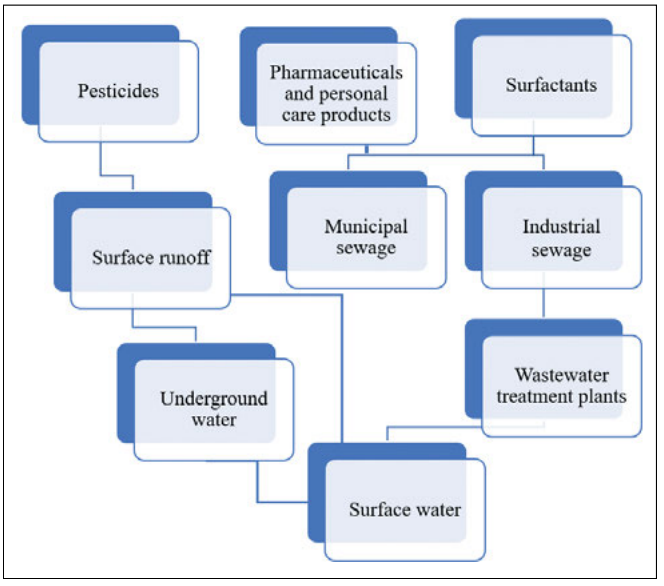

Figure 1. Sources of emerging contaminants in the environment
Rysunek 1. Źródła nowopojawiających się zanieczyszczeń w środowisku

pathogenic microorganisms rather than effectively targeting ECs. In water treatment processes, the problem is the formation of oxidation and disinfection by-products [6,7].

ECs pose a significant threat to aquatic environments and public health, even at low concentrations. Despite the lack of regulations regarding drinking water quality, there is an urgent need to monitor and understand the impact of these contaminants on the environment. The Water Framework Directive maintains an open list of ECs, with new substances continually emerging in both aquatic and terrestrial environments. There is also a risk that some compounds remain undetected, even by the most advanced analytical equipment [7].

The aim of this article is to provide a detailed characterization of organic emerging contaminants, analyze their potential impact on the natural environment and human health, and discuss current methods for removing these pollutants.

Characteristics of emerging contaminants

Division of emerging contaminants

The United Nations classifies emerging contaminants into several categories, considering various factors such as their chemical structure, environmental behavior, and potential impact on human health and ecosystems. Emerging contaminants are substances that have recently been identified as potentially harmful but have not yet been widely regulated or studied in depth. These can include both organic and inorganic compounds, and their categorization depends on their source, biological effects, and environmental persistence. The increasing recognition of these contaminants has led to a shift in how pollutants are perceived. While some of these substances, initially used in industrial and pharmaceutical products, were previously overlooked, ongoing scientific research has highlighted their potential negative impacts. This has changed our understanding of already known pollutants, uncovering previously underestimated aspects of their toxicity, prevalence, and effects on different environmental components [8]. The vast diversity in the chemical structure of EPs suggests that they interact with the environment in various ways, potentially causing different health and environmental consequences [9,10]:

- Personal hygiene products
  - Fragrances, UV filters, insect repellents, antiseptics, soaps, toothpaste, shampoos, creams, deodorants, hair dyes;
- Pharmaceuticals
  - Antibiotics, painkillers, anti-inflammatory drugs, psychiatric medications, β-blockers, lipid regulators, X-ray contrast agents, steroids, and hormones;
- Pesticides
  - Biopesticides, fungicides, insecticides, herbicides;
- Industrial and household products
  - Cleaning agents, degreasers, paints, aerosols, lubricating oils, bactericides, coatings, sealants, wood treatment products, solvents;
- Metals
  - Lead, cadmium, chromium, copper, mercury, nickel, and zinc;
- Surfactants
  - Nonionic, anionic, and cationic surfactants;
- Industrial additives and solvents
  - Dispersing agents, rheology modifiers, film-forming agents, wetting agents, surface modifiers, antifoaming agents, BTEX compounds (benzene, toluene, ethylbenzene, xylene), and chlorinated solvents [9,10].

On the other hand, based on their physicochemical properties, these substances are divided into organic substances, which include persistent bioaccumulative and toxic substances (PBTs), such as POPs (persistent organic pollutants), inorganic compounds (e.g., metals) [9,10].

Pharmaceuticals

Pharmaceutically active compounds (PhACs) can be categorized based on their mode of action, chemical structure, or therapeutic target. They are characterized by variable structures and the ability to be absorbed by living organisms, which makes them particularly hazardous. PhACs also have relatively short environmental half-lives, but their negative impact stems from the continuous input of these substances into aquatic ecosystems [1].

Additionally, in recent decades, there has been a sharp increase in pharmaceutical consumption. These compounds enter the environment primarily through wastewater from various sectors (hospitals, industry, agriculture, households). Since wastewater treatment plants (WWTP) are not designed to remove these compounds, they have been recognized as a major source of contamination. The treated effluent is then discharged into surface waters, making PhACs most commonly present in the aquatic environment. However, there is also a risk of pharmaceutical contamination of soils. During the wastewater treatment process, PhACs can adhere to the surfaces of microorganisms present in activated sludge, which is often used in agriculture as a fertilizer (Figure 2) [1,10].

Table 1 presents the classification of pharmaceuticals based on their use. These represent only a small portion of the wide range of drugs introduced into the environment, which can have negative effects on aquatic ecosystems.

Figure 2. Sources of pharmaceutical pollution; WWTP – wastewater treatment plant
Rysunek 2. Źródła zanieczyszczenia środowiska farmaceutykami; WWTP – oczyszczalnia ścieków

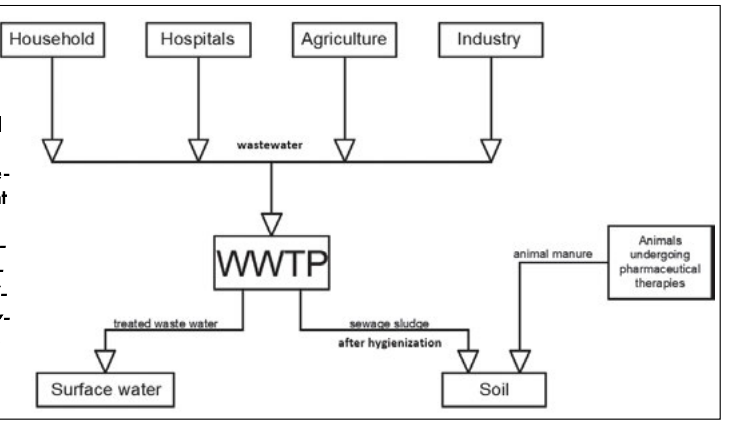

Table. 1. Classification of pharmaceuticals as pollutants in the aquatic environment [11]
Tabela 1. Klasyfikacja farmaceutyków jako zanieczyszczeń środowiska wodnego [11]

Type	Examples of substances
Painkillers and anti-inflammatories	Paracetamol, ibuprofen, diclofenac, naproxen, aspirin
Antidepressants	Fluoxetine, sertraline, amitriptyline, venlafaxine
Antibiotics	Norfloxacin, ofloxacin, ciprofloxacin, oxytetracycline
Anticoagulant	Warfarin, clopidogrel
Sedatives	Diazepam
Opioids	Morphine, codeine, tramadol
Antidiabetic drugs	Metformin

Analgesics and anti-inflammatory drugs can lead to a range of disturbances in aquatic organisms, including oxidative stress, metabolic disorders, DNA damage, and endocrine disruptions. The main health risks associated with the use of analgesics and anti-inflammatory drugs include depression, insomnia, hypertension, drowsiness, myocardial infarction, and acute ecotoxicological effects [1, 12].

The consumption of antidepressants can cause hypoglycemia, inhibition of aquatic organism growth, and acute or chronic toxicity. The main health risks associated with the use of antibiotics include heart arrhythmia, liver dysfunction, and immune system disorders. The presence of antibiotics can lead to the spread of antibiotic resistance genes (ARGs). Even low concentrations of pharmaceutical drugs are sufficient to trigger antibiotic resistance and can have harmful effects on newborns, the elderly, and patients with kidney and liver failure. Furthermore, antibiotics can significantly impair the functioning of biological wastewater treatment plants, as they destroy and inhibit the development of microorganisms involved in the purification processes. It has been shown that metformin, used in the treatment of diabetes, has the ability to bioaccumulate in the roots and leaves of plants, and it is highly mobile in the soil. Diazepam, on the other hand, causes growth disturbances and weight loss in mussels. In crustaceans, it affects the nervous system and behavior, which can significantly increase the risk of predation. It also alters swimming patterns in fish and changes behavioral traits in polychaetes. Exposure to warfarin in juvenile Senegalese saltwater fish led to hemorrhaging, increased oxidative stress, and impaired liver function. The use of opioids can affect subsequent generations through genetic changes and biological mechanisms that modify the response to morphine withdrawal [13, 14].

Toxicity, teratogenicity, and genotoxicity of pharmaceuticals to aquatic organisms lead to developmental disorders, genetic mutations, and the death of many species. They also contribute to coral reef bleaching, which threatens marine biodiversity. Pharmaceuticals negatively affect reproductive practices, causing problems in the reproduction of fish and other aquatic organisms. The phenomena of bioaccumulation and biomagnification cause these substances to accumulate in the tissues of organisms at higher levels of the food chain, which can lead to genotoxic effects and organ damage, such as to the testes, adrenal glands, thyroid, and liver. As a result, reproductive and digestive system damage may occur, as well as antibiotic resistance and neurological system damage [13, 14].

Personal hygiene products

Personal hygiene products are a category of items intended for self-care, used to maintain cleanliness and body care. Emerging contaminants found in these products can have various sources. Some are directly present in the formulation of these products, while others may form as a result of their breakdown or reactions in the environment [14]. Direct exposure to these substances can occur through inhalation, skin contact, ingestion, and absorption. Similar to pharmaceuticals, personal hygiene products primarily enter the environment through contaminated water. Once released into the environment, these substances can negatively impact living organisms. For animals and plants, they can disrupt vital functions, cause behavioral changes, reproductive problems, and even death. In humans, uncontrolled exposure to these substances can lead to various health problems, such as allergies, skin irritation, endocrine and reproductive disorders, and even cancer. Most personal care products are potentially carcinogenic, damage the hormonal system, and can contribute to obesity, diabetes, and infertility. It has been shown that triclosan alters placental weight, causes developmental defects in the fetus, leads to focus problems in children, and affects blood pressure. Furthermore, it causes hormonal changes, including early onset of menstruation and polycystic ovary syndrome, and has negative effects on the kidneys. The occurrence of endometriosis and uterine fibroids has been linked to benzophenone, a UV filter component. In men, this substance, as it is excreted in urine, reduces sperm motility and maturity, contributing to fertility issues. Parabens also negatively affect male fertility by shortening sperm lifespan and have been linked to breast cancer in women [15, 16].

Table 2 presents the most common contaminants along with examples of personal hygiene products in which they can be found. Personal hygiene products contain surfactants and phthalate esters (phthalates), which constitute a separate group of emerging contaminants [14].

Table. 2. Examples of personal care products containing emerging contaminants
Tabela 2. Przykłady produktów do pielęgnacji ciała zawierających nowopojawiające się zanieczyszczenia

Type	Examples of substances	Examples of personal hygiene products	Bibliography
Disinfectants	Triclosan, chlorhexidine	Disinfectants, antibacterial soaps, toothpastes, antiseptics	[17]
UV filters	Benzophenone-3, octocrylene, avobenzone, octisalate	Sunscreens, cosmetics with UV filter	[18]
Preservatives	Parabens (methyl-, ethyl-, benzyl, propyl-, butylparaben)	Shampoos, conditioners, skin care cosmetics, lipsticks, face washes	[19]

Surfactants

Surfactants, also known as surface-active agents, are chemical compounds that reduce the surface tension of liquids, enabling better wetting of surfaces and emulsifying fats. They are amphipathic molecules that contain both hydrophilic components, which interact with water, and hydrophobic components, which do not interact with water. Surfactants are widely used in various industrial and everyday products, including detergents, cosmetics, cleaning agents, emulsifiers, solvents, foaming agents, and stabilizers (Table 3) [20]. Shampoos, shower gels, soaps, toothpastes, and other personal hygiene products contain different types of surfactants. In the pharmaceutical industry, surfactants are used to prepare syrups, capsules, and injectable formulations. Their role in dissolving drugs is crucial for improving their bioavailability and absorption by the body. The chemical industry uses surfactants in the production of paints, adhesives, cleaning agents,

Table 3. Division and application of surfactants [22,23]
Tabela 3. Podział i zastosowanie surfaktantów [22,23]

Surfactant type	Examples	Applications
Anionic	SDS (sodium dodecyl sulfate) LAS (linear alkylbenzene sulfonate) SLS (sodium lauryl sulfate)	Detergents, cleaning agents, cleansing shampoos, laundry detergents, fabric softeners, personal hygiene products
Cationic	CTAB (cetyltrimethylammonium bromide) QAC (quaternary ammonium compound) CPC (cetylpyridinium chloride)	Fabric softeners, cosmetics, disinfectants, antistatic fluids
Non-ionic	APE (alkylphenol ethoxylate) AE (alcohol ethoxylate) FAE (fatty acid ethoxylate) APEO (etoksylany alkilofenoli)	Emulsifiers in cosmetics, industry, detergents, wetting agents, cleaning agents, fabric softeners, shampoos
Amphoteric	AO (amine oxide), Betaine	Body care products, shampoos

detergents, and dishwashing liquids. The use of surfactants in these products aims to enhance their surface properties, stabilize emulsions, and improve their cleaning efficiency [21].

Surfactants primarily enter the environment through municipal and industrial wastewater. Similar to pharmaceuticals and personal hygiene products, they are not completely removed during wastewater treatment processes, leading to their presence in surface and groundwater. Additionally, the use of surfactants in agriculture, for instance as adjuvants in pesticides, contributes to their direct introduction into the soil. Human exposure to these substances occurs through several main pathways, including the consumption of contaminated water or food that has come into contact with polluted water or soil, the use of cosmetics and cleaning products containing surfactants, and the inhalation of aerosol particles containing surfactants when using sprays or aerosol products. Plants can absorb surfactants through their roots from contaminated soil or water. Aquatic animals are exposed to surfactants through direct contact with polluted water. In terrestrial animals, exposure may occur through the consumption of contaminated water or food. Plants exposed to high concentrations of surfactants may display inhibited growth, reduced resistance to environmental stress, damage to the root system, and decreased photosynthetic ability. Surfactants also contribute to the eutrophication of water bodies. In amphibians, mammals, and fish, they can cause endocrine disruptions. Surfactants can damage the protective mucus layer and gills, and at concentrations around 5 ppm, fish eggs can die. Additionally, it has been observed that some individuals may change sex from male to female, complicating reproduction. For humans, prolonged exposure to surfactants can lead to skin, eye, and respiratory tract irritations. There is also evidence that some surfactants may cause hormonal and metabolic disturbances. However, there is a positive aspect to the use of surfactants; they have been shown to be effective in cleaning wastewater and soil from other emerging contaminants such as heavy metals, personal hygiene products, and pharmaceuticals [24,25].

Pesticides

Pesticides are among the most persistent chemicals that bioaccumulate and biomagnify in water and soil environments. Their presence in ecosystems results from intensive use in agriculture, horticulture, and urban areas. They are designed to repel, destroy, prevent and mitigate pests, mainly to improve food availability and safety and reduce disease transmission [23]. However, they have been shown to cause toxicity to humans and other organisms. Pesticides enter the environment in a variety of ways: through direct spraying of crops, surface runoff from fields, spray drift, and penetration into soil and groundwater. Aerosols inhalation, ingestion of contaminated food and water, and dermal contact with contaminated surfaces are the most common routes of exposure. Plants can absorb pesticides through their roots and leaves, whereas animals and humans are exposed by ingestion of contaminated vegetation and water, as well as by contact with contaminated soil and air. Pesticides are classified according to their mode of application and the type of pest they are intended to control (Table 4) [26,27].

Table 4. Types of pesticides [26,27]
Tabela 4. Rodzaje pestycydów [26,27]

Type of pesticide	Examples	Purpose of use	Mechanism of action
Insecticides	Aldicarb, carbaryl, pyrethroids	Insect and vertebrate control	Nervous system disorders
Herbicides	Glyphosate, atrazine	Weed destruction	Inhibition of photosynthesis or growth
Fungicides	Mancozeb, chlorothalonil, azoxystrobin	Protection against fungi	Inhibiting mitochondrial respiration, inhibiting growth
Rodenticides	Warfarin, bromadiolone	Rodent Control	Disruption of the blood clotting process

Pesticides pose a threat to nontarget species and disrupt the balance of ecosystems. In humans, long-term exposure to pesticides can cause a number of health problems, including cancer, hormonal disorders, damage to the nervous system, and developmental defects in children. Exposure to these substances is associated with Parkinson's disease and cytogenetic damage. The uncontrolled use of pesticides is particularly dangerous and can result in acute poisoning manifested by nausea, vomiting, headaches, and in extreme cases even death. Water pollution with pesticides can affect aquatic ecosystems, cause the death of aquatic organisms, and disrupt natural ecological processes. Pesticides with a long half-life can remain in the soil for a long time, affecting its quality and the ability to cultivate. This can lead to the accumulation of these substances in the food chain [28].

Microplastics

Microplastics are polymer particles with a diameter ranging from 1 μm to < 5 mm, which pose an increasingly serious threat to aquatic ecosystems and human health. Their characteristics make them difficult to detect and remove from water. In 2020, global plastic production reached a significant level of 367 million tons. The current figure does not include the production of recycled plastics [29].

Microplastics in water come from a variety of sources. One of them is the breakdown of larger plastic fragments that end up in the natural environment as a result of waste disposal (e.g. fishing nets constitute about 46% of this waste in the marine environment) and then undergo the process of fragmentation/degradation under the influence of weather conditions and the action of the sun. In addition, artificial packaging, foils and plastic bags, which, if not properly managed, can easily get into rivers and seas [29]. In addition to their impact on drinking water, microplastics also penetrate aquatic ecosystems, where they affect aquatic organisms such as fish, crustaceans, and mollusks. Due to their small size and often attractive color, microplastics can be considered food. This process can lead to the accumulation of toxic substances at subsequent trophic levels affecting the food chain and the quality and safety of aquatic foods. Microplastics in the soil environment come mainly from sewage and the process of mulching and composting, in which plastic films and various wastes are constantly decomposed, creating microplastics and nanoplastics, which then migrate to plants, fruits and vegetables, thus affecting animals and their products, including meat and milk. As a result of these processes, microplastics accumulate in food. Irresponsible disposal of plastic waste by people also causes microplastics to appear in the air environment, floating in the atmosphere, migrating to various places and becoming a source of air pollution [30]. Another source of microplastics are cosmetic and hygiene products, such as face creams, scrubs, or toothpastes, which contain microplastic microbeads or fibers. After using and rinsing these products, microplastics end up in the sewage system and consequently in the aquatic environment [31]. In the Atlantic, as in other oceans, there is an area known as the "Great Garbage Patch," where various types of waste, including microplastics, accumulate. This garbage patch is an area of the ocean where, as a result of ocean currents, wind, and human activity, contaminants concentrate into a large-scale collection of garbage. The Great Atlantic Garbage Patch is one of the largest collections of microplastics in the world [32].

Microplastics has become a global and complex problem. Due to chemical stability, plastic microparticles are stable in an aqueous environment and remain there for thousands of years [33]. The systematic influx of microplastics into natural water reservoirs is a threat to plants, animals, and people. This phenomenon causes irreversible and dangerous changes in the aquatic environment. The micrometric elements of plastic find their way into the food chains of aquatic organisms. Microplastics have a high specific surface area because of their small particle size. The microplastics present in water reservoirs absorb and transport many toxic substances, such as polycyclic aromatic hydrocarbons, pesticides, detergents, and heavy metals. An example of substances sorbed on the surface of microplastics is polychlorinated biphenyls. The analysis of the samples showed that the microplastics contain polychlorinated biphenyls at concentrations 10^5-10^6 times higher than in the surrounding seawater. Ingestion of such microplastics by organisms can increase the desorption of contaminants, increasing their bioavailability and toxicity [31,34].

Furthermore, plastic becomes toxic through additives. Heavily degraded and fragmented plastic provides many attachment sides for lipophilic contaminants, pathogens, and toxic metals that can be transported across the world attached to the plastic surface. It is suspected that predominantly microplastics, with a large surface-to-volume ratio, act as a preferred vector for contaminants. Microplastics, because of their tiny particle size, easily can be mistaken for food by aquatic organisms. Moreover, additives play an important role as harmful products when leached from microplastics during their degradation. These included bisphenol A and phthalates, which are added as plasticizers to plastic. MPs can also release additives or monomers used for manufacturing [35,36].

Plasticizers

Plasticizers are key components of many industrial and household products. The role of plasticizers is to increase the flexibility, durability, and plasticity of plastics. These include, for example, compounds from the alkyl phenol group (bisphenol A, 4-octylphenol, 4-nonylphenol) or substances from the phthalic anhydride group (phthalates) (Table 5) [27].

Table 5. Characteristics of selected commonly used phthalates [37,38]
Tabela 5. Charakterystyka wybranych powszechnie stosowanych ftalanów [37,38]

Name	Abbreviation	Chemical formula	Molar mass [g/mol]	Solubility in water, at 25°C [g/dm^3]	K_{OW} Log
Dimethyl phthalate	DMP	$C_{10}H_{10}O_4$	194.2	<0.100	1.64
Diethyl phthalate	DEP	$C_{12}H_{14}O_4$	222.2	1	2.70
Di-n-butyl phthalate	DBP	$C_{16}H_{22}O_4$	278.3	0.015	4.83
Diisobutyl phthalate	DIBP	$C_{16}H_{22}O_4$	278.3	0.011	4.46
Butylbenzyl phthalate	BBP	$C_{19}H_{20}O_4$	312.4	<0.002	5
Di-n-octyl phthalate	DNOP	$C_{24}H_{38}O_4$	390.6	<0.001	7.73
Di(2-ethylhexyl)phthalate	DEHP	$C_{24}H_{38}O_4$	390.6	<0.001	8.71
Diisononyl phthalate	DINP	$C_{26}H_{42}O_4$	418.6	<0.001	8.60
Diisodecyl phthalate	DIDP	$C_{28}H_{46}O_4$	446.7	<0.001	10.47

The addition of plasticizers to polymers allows for the change in their physical properties, which allows for more versatile applications. Thanks to plasticizers, plastics become more flexible and easier to form, which in turn allows the production of products with various shapes and applications [27]. Global production of phthalates has been steadily increasing, reaching 1.9 million tons in 1975, 6.2 million tons in 2009 and more than 8 million tons in 2011 [39]. There are more than 1200 different phthalates known, but only 50 to 100 substances are of commercial importance and are used, among others, in the production of almost 60 polymers and 30 product groups [40]. The widespread use of phthalates in industrial processes and consumer products (Table 6) results in their presence in the natural environment.

The release of phthalates and their increased availability in the environment is often associated with the fragmentation and degradation of plastics. Many scientific studies suggest that some phthalates can act as endocrine disruptors, disrupting the hormonal functions of

Table 6. Application of selected phthalates [41]
Tabela 6. Zastosowanie wybranych ftalanów [41]

Phthalate	Application
DEHP	Medical tubing containing PVC, blood bags, medical devices, food packaging, plastic toys, wall hangings, tablecloths, floor tiles, furniture upholstery, shower curtains, garden hoses, pool liners, rainwear, children's clothing, dolls and some toys, shoes, car upholstery, foils and packaging sheets
DEP i DBP	Nail polishes, deodorants, perfumes, pharmaceuticals, insecticides
DNOP	Toys
BBP	Vinyl flooring, adhesives, sealants, food packaging, furniture upholstery, vinyl tiles, carpet tiles and faux leather
DMP	Insecticides, adhesives, hair styling products, shampoos, aftershaves

the body, interfering with sexual development, causing fertility problems and metabolic disorders [41]. As research into the impact of plasticizers on health and the environment continues, manufacturers are taking steps to replace harmful phthalates with safer alternatives.

ECs removal methods

The constantly increasing requirements for the protection of the natural environment encourage the search for new effective, economically attractive, and environmentally friendly technologies for water and wastewater treatment. Removing emerging contaminants from water and sewage is a problem that is still receiving a lot of attention. A particularly difficult issue is the removal of organic compounds that are difficult to decompose, for which conventional methods of water or sewage treatment are ineffective and it is necessary to use additional solutions. The negative impact of micropollutants on the condition of the aquatic environment and their common occurrence require the development of new treatment technologies and/or the optimization of existing processes [42]. The methods of removing emerging contaminants can be divided into conventional (physicochemical) methods and advanced oxidation methods. Physical and chemical processes include removal by membrane techniques, coagulation and flocculation, and adsorption [43].

Traditional methods of removing contaminants from wastewater and drinking water, such as activated sludge technology, can partially contribute to the removal of ECs. However, their complete removal is a challenge due to the great diversity, unique characteristics, and extremely low concentrations of these substances. The biological treatment method usually involves the use of one of two main technologies: activated sludge or biological filter. The main way of eliminating ECs during biological treatment is through biodegradation and adsorption. The presence of aerobic bacteria and other microorganisms plays a key role during the oxidation process and the fusion of organic matter cells. However, they need a sufficient amount of oxygen to effectively carry out the process [44]. Biological filters are generally equipped with a tank filled with filter material on which a biological film develops, while the activated sludge method is a process in which bacteria and microorganisms are combined with sewage. The removal efficiency of 18 different ECs from 42 WWTPs was studied in five different regions of India using different treatment techniques, including trickling filter. Using a trickling filter, an effective removal of ofloxacin, dichlofenac and ibuprofen was observed, but no removal of ampicillin, ciprofloxacin and naproxen was observed. These ECs classified in the same category have similar physical, chemical, and biological parameters, but as the study results indicate, these contaminants cannot always be removed using a single technique [45].

Adsorption is a process of binding a mass of a substance between two phases, specifically the attraction of a gaseous substance to the surface of a liquid or solid substance or the attraction of a liquid substance to the surface of a solid substance. Adsorbents are used to adsorb pollutants from wastewater using intermolecular forces. We distinguish two types of interactions between the solid surface and adsorbates: physisorption, or physical adsorption, and chemisorption, or chemical adsorption. Although adsorption is a simple and effective method, it is associated with high operating costs associated with the use of commercial adsorbents such as activated carbon, minerals or natural clays. In order to reduce costs and environmental impact, scientists have developed various alternative adsorbents derived from agricultural and industrial wastes that can replace commercial adsorbents. The use of an economical and easily accessible adsorption-based process can be a real alternative for the treatment of wastewater containing ECs. The key element ensuring the maximum removal of various types of pollutants is the appropriate selection of the adsorbent, depending on the characteristics of the adsorbent and the adsorbate [46]. The list of agricultural wastes as potential adsorbents for the removal of different types of ECs is summarized in Table 7.

Membrane technologies are one of the methods of removing ECs from water. This technology uses both biological processes in membrane bioreactors and physicochemical processes such as reverse osmosis, ultrafiltration, and nanofiltration. Membrane bioreactors are a combination of membrane-based filtration processes, such as microfiltration or ultrafiltration systems, with biological reactors with suspended growth. Currently, they are the most commonly used processes for obtaining relatively clean water from wastewater, combining

Table 7. Agricultural wastes as absorbents for the removal of various types of ECs
Tabela 7. Odpady rolnicze jako absorbenty do usuwania różnych rodzajów EC

Agricultural waste	Examples of pollution	Literature
Bamboo chips, corn cobs, eucalyptus bark, rice chaff and rice straw	Pesticides (atrazine and imidacloprid)	[47]
Rice chaff	Metal ions (Fe, Pb and Ni); personal hygiene products and veterinary drugs (tetracycline)	[48]
Coconut fiber dust	Dye (methylene blue)	[49]
Coconut shell	Dye (Rhodamine-B)	[50]
Wood chips	Phenol	[51]
Wooden sawdust	Metal ions (Co, Ni, Cu and Zn)	[52]
Orange, pomelo and passion fruit peels	Dyes (Rhodamine-B; Methylene Blue)	[53]
Pomegranate peel	Metal ion (copper)	[52]
Peach pits	Stimulant (caffeine), anti-inflammatory drug (diclofenac), and psychiatric drug (carbamazepine); dye (methylene blue); metal ion (platinum)	[54]

membrane and biological processes [55]. Membrane technologies such as reverse osmosis, nanofiltration, microfiltration, and ultrafiltration use high pressure to filter contaminants from water. These are the most commonly used membrane techniques for water purification. This method is constantly being improved or modified to further improve performance and use. Membrane processes are particularly effective in removing turbidity and microbiological contamination. However, high operating costs limit the full use of this technology, and in addition, membranes are easily fouled, which can result in unexpected interruptions in the purification process [56].

An advanced oxidation method including ozonation, H_2O_2/UV, Fenton reactions, ultrasound, photocatalytic and electrochemical oxidation can help effectively remove ECs [57]. With this method, the target contaminants can be quickly and efficiently converted into inorganic compounds such as CO_2 and H_2O. Among the advanced oxidation methods used to remove or reduce the concentration of some hormones and personal care products from wastewater, the most promising technique is ozone oxidation [58]. Low concentrations of ECs, which pose a challenge to the advanced oxidation method, result in slow reaction rates and poor efficiency. In order to oxidize trace amounts of ECs, large amounts of oxidants are required, leading to increased operating costs. Additionally, under suboptimal conditions, this method can generate toxic intermediates or by-products. A common disadvantage of all advanced oxidation methods is the high operating cost. However, with the advent of higher efficiency UV lamps, visible light catalysts and improved reactor design, and with the help of computational fluid dynamics and energy modeling, there is a greater chance of successful implementation of this method on a large scale [59].

Summary and conclusions

The issue of emerging contaminants is an urgent and important problem that requires a comprehensive approach. Their impact on human health and the environment is significant because these substances penetrate groundwater and surface water, enter the food chain, and accumulate in organisms. ECs are toxic, mutagenic, and carcinogenic, which poses a threat to aquatic organisms and people using water for consumption. The ECs present in the environment cause indisputable long-term ecological effects. The difficulty in detecting and removing these contaminants requires the development and implementation of advanced technologies and analytical methods that allow for the complete removal of hazardous substances. The introduction of effective monitoring systems is crucial for the assessment of risk and protection of water and public health. The analysis carried out showed several important conclusions:

- It is necessary to continue research on the hazardous, bioaccumulation and impact of ECs on aquatic organisms and humans in order to develop precise guidelines and standards for these substances,
- The introduction of legal regulations restricting the use of hazardous substances is necessary to protect the aquatic environment and public health,
- Collaboration between scientific, regulatory, industry and community sectors are key to identifying, eliminating and preventing the impact of ECs on water resources,
- The introduction of innovative purification technologies is key to combating the threats associated with ECs,
- Global action is essential to effectively protect water resources and ensure a safe source of water for future generations.

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