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Review

Organophosphate esters in ecosystems: environmental migration, bioaccumulation, and human health risks

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Abstract. The article provides a review of current data on a group of organophosphate esters, widely used as flame retardants and plasticizers. It systematizes information on their sources, pathways of entry into ecosystem components and the human body, as well as the toxic effects they cause, ultimately leading to ecosystem sustainability disruption. Based on the synthesis of primary data, conclusions are drawn regarding the constant emission of organophosphate esters from most polymer-containing materials, in addition to their persistence, bioaccumulation, and high toxicity to living organisms at different trophic levels. The necessity of studying the migration of organophosphate esters in various ecosystems is emphasized, as well as systematic monitoring of their levels in agricultural products and consumer goods.

Keywords: organic esters of phosphoric acid, flame retardants, ecosystem sustainability, living organisms, food chains, toxic effects

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Научный обзор

Органические эфиры ортофосфорной кислоты в экосистемах: миграция в средах, биоаккумуляция и угрозы для здоровья человека

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Аннотация. В статье дан обзор современных данных о группе органических эфиров ортофосфорной кислоты, широко применяемых в качестве антипиренов и пластификаторов. Систематизирована информация об их источниках, путях поступления в компоненты экосистем и организм человека и вызываемых ими токсических эффектах, в конечном итоге приводящих к нарушению устойчивости экосистем. На основании обобщения первичных данных сформулированы выводы о наличии постоянной эмиссии органических фосфатов из большинства полимерсодержащих материалов, их персистентности, биоаккумуляции и высокой токсичности для живых организмов различных трофических уровней. Сделан вывод о необходимости исследования миграции органических фосфатов в различных экосистемах, а также систематического контроля их содержания в сельскохозяйственной продукции и потребительских товарах.

Ключевые слова: фосфорорганические эфиры, антипирены, устойчивость экосистем, живые организмы, трофические цепи, токсические эффекты

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Introduction

The rapid growth in the production of plastics that are used across a wide range of sectors in the global economy and the high flammability of many polymeric materials necessitate the use of flame retardants in their production. In many cases, flame retardants also serve as plasticizers. Until relatively recently, polybrominated diphenyl ethers (PBDEs) were widely used for this purpose. Their initial use began in the 1970s, when they were involved in the manufacture of furniture, children's clothing, electronic equipment, and automotive products (Blum et al., 2019). As a result of subsequent studies, it was concluded that the bioaccumulation and toxicity of PBDEs to humans and the environment were unacceptably high, which led to their gradual usage phase-out (Liu et al., 2024). Currently, the use of PBDEs is largely prohibited following their inclusion in the list of hazardous substances under the Stockholm Convention on Persistent Organic Pollutants.¹ Nevertheless, residual amounts of these compounds in the environment continue to pose a threat to the health of ecosystems in general and humans in particular (Dou and Wang, 2023).

For several years, organophosphate esters were considered a good alternative to PBDEs. However, an increasing number of scientific works demonstrates their adverse effects and widespread occurrence in the environment; consequently, this substitution has proven to be less effective than initially anticipated (Castro-Jimenez et al., 2022).

Organophosphate flame retardants (OPFRs) represented by organic esters of phosphoric acid or organophosphate esters (OPEs) – are a class of chemical compounds commonly used in the production of a broad range of consumer and industrial products, from construction materials to children's toys and daily care products, as flame retardants and plasticizers. OPEs are widely used in numerous industrial sectors. Global consumption of OPEs increased from 186 000 t in 2001 to 1 million t in 2018 (Ai et al., 2024; Fu et al., 2020). In 2022, worldwide flame retardant consumption exceeded 2.7 million t, with phosphorus flame retardants accounting for 28% of this volume (Du, 2024). According to projections of the United Nations in the report 'Global Chemicals Outlook II'², annual global plastic production, characterized by the extensive use of OPEs, is expected to reach 2 billion t by 2050 (Alpizar, 2019).

OPEs are typically present in materials as additive compounds that do not form chemical bonds with the components of the material matrix (Tudor, 2022). Due to this, OPEs can be easily released from everyday products, resulting in their emission into the environment. They are distributed in various matrices: soils (Ma et al., 2022), the atmosphere (Na et al., 2020), surface waters (Marlina et al., 2024), groundwater (Ai et al., 2024), and sediments (Castro-Jimenez et al., 2022), as well as in industrial and municipal wastewater and indoor dust (Dou and Wang, 2023; Tudor, 2022). In addition, OPE's presence has been registered in human tissues and biological fluids, including hair (Wang et al., 2023), blood serum (Hou et al., 2023), urine (Dang et al., 2023), breast milk, and placenta (Kim et al., 2014; Sundkvist et al., 2010).

Organophosphate ester exposure of humans occurs through inhalation of indoor air and dust. Significant concentrations of these compounds are also now frequently recorded in drinking water and food products – from natural ecosystems OPEs can be transferred into living organisms, where they accumulate and concentrate along each level of food chains (Gbadamosi et al., 2021; Zhang et al., 2022).

Growing evidence of the adverse effects associated with OPEs industrial usage has led several countries to introduce partial restrictions³ on specific flame retardants from this group in consumer products (Bash, 2025; Tudor, 2022). Moreover, Russia has already established regulatory norms for a number of OPEs (TCEP⁴ and TCPP⁵).

¹ United Nations Environment Programme (UNEP), 2012. Guidance on best available techniques and best environmental practices for the recycling and disposal of articles containing polybrominated diphenyl ethers (PBDEs) listed under the Stockholm Convention on Persistent Organic Pollutants.

² United Nations Environment Programme, 2019. Global Chemicals Outlook II: from legacies to innovative solutions – implementing the 2030 Agenda for Sustainable Development – Synthesis Report. Web page. URL: <https://wedocs.unep.org/items/e36200ba-de99-43ca-a6c2-db3704c9b7f0> (accessed: 18.10.2025).

³ California Health and Safety Code, 1986. Safe Drinking Water and Toxic Enforcement Act. Proposition 65. Web page. URL: <https://www.p65warnings.ca.gov/fact-sheets/tris2-chloroethyl-phosphate-tcep> (accessed: 10.09.2025).

⁴ Tris(2-chloroethyl)phosphate. Federal Register of Potentially Hazardous Chemical and Biological Substances of the Russian Federation. Regulations on TCEP. Web page. URL: <https://www.rpohv.ru/online/detail.html?id=927> (accessed: 09.09.2025)

⁵ Tris(2-chloropropyl)phosphate. Federal Register of Potentially Hazardous Chemical and Biological Substances of the Russian Federation. Regulations on TCPP. Web page. URL: <https://www.rpohv.ru/online/detail.html?id=2800> (accessed: 09.09.2025).

As for China, the world's largest consumer goods manufacturer, no regulatory limitations on the OPEs' usage in production have been implemented to date. At the same time, recent studies by Chinese researchers increasingly emphasize concerns about the environmental persistence of OPEs and their high concentrations in various ecosystem components (Dou and Wang, 2023; Fu et al., 2020; Lai et al., 2019; Li et al., 2023; Zhang et al., 2022).

Russian research of this kind remains extremely limited, despite the presence of manufacturers using OPFRs in their industrial processes and the extensive Russian market for Chinese consumer products. At present, there is a growing public and expert concern about OPFRs' presence in the environment in Russia; however, comprehensive scientific databases and results from model and field experiments comparable to those available internationally are largely lacking for Russian ecosystems. Information available through online resources is largely fragmented and consists of translated material from foreign sources^{6, 7, 8}. Existing Russian scientific publications (Pleshakova and Gusev, 2024; Polyakova and Lebedev, 2019) provide only the mention of organophosphate esters' existence and shortly document their occurrence in natural environments as well as some toxic effects they cause. Nevertheless, these studies do not comprehensively address the full range of toxicological and environmental aspects required for an adequate risk assessment.

The present review aims to systematize available information on the sources and routes of organophosphate ester entry into natural ecosystems and the human body. A brief overview of the OPEs group is provided, with particular attention to their effects on living organisms.

Research objects and methods

For this scientific review, a comprehensive analysis of 55 sources was conducted, including publications in peer-reviewed international and Russian journals published over the past two decades, as well as regulatory and expert reports from international organizations (UN, EPA, ATSDR, ECHA, etc.) and legislative acts. The sources also included electronic databases such as Scopus, Web of Science, PubMed, specialized platforms (ScienceDirect, SpringerLink, MDPI, Wiley Online Library), and official government online resources^{3, 4}. Priority was given to publications presenting recent data on organophosphate esters and their impacts on ecosystems in different countries to highlight their ubiquitous presence and the global concern of the research community about this problem. The review included the most informative and representative results, which clearly demonstrate the environmental hazards associated with the presence of these compounds in the environment and highlight the need for further investigation of their effects on human health and ecosystems.

General characteristics of OPEs

The group of organophosphate esters is a group of synthetic organic esters, derivatives of phosphoric acid, compounds sharing a common basic phosphate group and various substituents (Table 1) (Ai et al., 2024). Depending on the nature of these substituents, OPEs may be either non-halogenated or halogenated phosphoric acid esters (Dowbysz et al., 2023). Accordingly, OPEs are commonly divided into three main categories: chlorinated esters (Cl-OPEs), alkyl OPEs, and aryl OPEs (Ai et al., 2024).

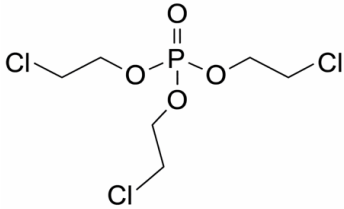
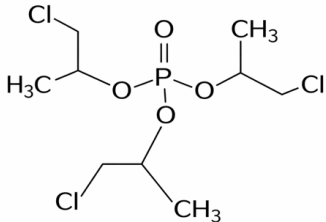
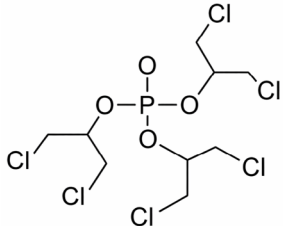
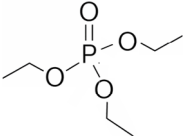
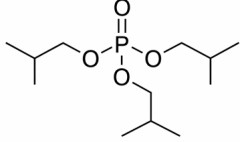
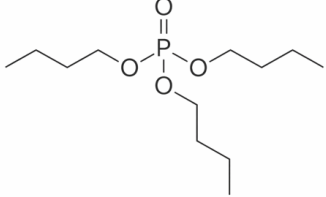
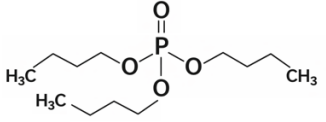
Table 1 presents the OPE compounds most frequently mentioned in international studies (Bika et al., 2022; Dang et al., 2023; Lao et al., 2024; Zhang et al., 2022; and others). It should be noted that the OPE group includes over twenty other compounds with different substituents, less common in the scientific literature. OPE compounds are grouped in the table below according to the nature of the substituents.

⁶ Fire retardants remain a toxic problem in homes (In Russian). Web page. URL: https://zoom.cnews.ru/rnd/news/top/antipireny_poprezhnemu_ostayutsya_toksichnoj_problemoj_zhilishch (accessed: 11.09.20).

⁷ 'Harmless' polymer additives pose a potential threat to children's brains (In Russian). Web page. URL: <https://scfh.ru/news/bezvreidnye-dobavki-k-polimeram-potentsialnaya-ugroza-detskomu-mozgu/> (accessed: 11.09.2025).

⁸ The use of flame retardants in children's products and upholstered furniture is being banned worldwide (In Russian). Web page. URL: <https://ecoidea.me/ru/article/1242> (accessed: 12.09.2025).

Table 1. List of the main OPEs used as fire retardants and plasticizers.

Compound name	CAS number	International abbreviation	Structural formula
Chlorinated organophosphate esters			
Tri(2-chloroethyl) phosphate	115-96-8	TCEP	
Tri(chloropropyl) phosphate	13674-84-5	T CPP	
Tris(1,3-dichloroisopropyl) phosphate	13674-87-8	TDCPP	
Group with alkyl substituents			
Triethyl phosphate	78-42-2	TEP	
Tri-isobutyl phosphate	126-71-6	TiBP	
Tri-n-butyl phosphate	126-73-8	TnBP	
Tributyl phosphate	126-73-8	TBP	

Compound name	CAS number	International abbreviation	Structural formula
Tributoxyethyl phosphate	78-51-3	TBEP	
Tris(2-butoxyethyl) phosphate	78-51-3	TBOEP	
Trimethyl phosphate	512-56-1	TMP	
Tris(2-ethylhexyl) phosphate	78-42-2	TEHP	
Group with aryl substituents			
2-ethylhexyl diphenyl phosphate	298-07-7	EHDPP	
Triphenyl phosphate	115-86-6	TPhP	

In different materials, specific types of OPEs are used for different purposes. Halogenated OPEs serve as flame retardants, they act in the gas phase, releasing bromine or chlorine radicals that reduce the reaction promoting fire spread. Non-halogenated flame retardants are used as both plasticizers and flame retardants, but they act differently – in the solid phase, they help reduce oxygen levels and promote the formation of a protective char layer, and thereby slow fire growth. Research shows that halogenated flame retardants are generally more effective at inhibiting fire (Tudor, 2022).

The rapid growth of polymer production and consumer demand is driving an increasing need for functional additives that enhance material qualities. Among these additives, OPEs play a key position in the manufacture of plastics, construction, and other composite materials. Organophosphate esters are used on an industrial scale due to their relatively low cost and, at the same time, their unique combination of performance characteristics: solvent resistance, stability, and good water resistance. However, OPEs are not chemically bound to the materials where they were added to improve their properties, so they are easily released into the environment, where they pose a hazard to humans, plants, and animals (Bika et al., 2022).

Organophosphate esters behavior in ecosystems is governed by their physicochemical properties, including water partition coefficient (log K_{ow}), solubility, and vapor pressure. These parameters determine their volatility, sorption activity, and potential for bioaccumulation and biomagnification, (accumulation abilities while moving through the food chain from source to end user). Throughout the life cycle of products containing OPEs, these additives may be released through various processes, including volatilization, leaching, abrasion, and dissolution (Tudor, 2022). As a result, OPEs are continuously emitted from furniture, plastic materials, vehicles, and industrial activities into the air and subsequently enter natural ecosystems.

It should be noted that over 1 000 t of flame retardants are still produced annually in Europe (Castro et al., 2023), and the majority of these are presented by widely used OPEs. In the United States, the production volume of TCPP was estimated at approximately 54 million pounds in 2012, equivalent to about 24 000 t⁹. China represents one of the world's largest producers and consumers of OPEs, with annual production of approximately 0.36 million t in 2020, a figure that continues to increase (Wang et al., 2023).

Sources of OPEs

Sources of OPEs include industrial facilities, such as organophosphate ester production plants, plants using flame retardants in their manufacturing processes, and facilities engaged in the recycling and disposal of electronic and other types of waste (Chen et al., 2021; Qi et al., 2019), as well as municipal wastewater treatment plants and industrial wastewater treatment systems (Kristanti et al., 2023; Marlina et al., 2024), and leachates from construction and municipal waste accumulation sites (Ma et al., 2022; Stelzer et al., 2024).

Studies have shown that OPEs are widespread in the atmosphere and water bodies, and due to their high solubility and mobility, these compounds can be transported into natural ecosystems via air and water masses. The main processes facilitating the transfer of OPEs into air and water are diffusion, sedimentation, and volatilization. Atmospheric precipitation, formed through air-water exchange, is the primary pathway for OPEs to enter the environment and ecosystems (Marlina et al., 2024). Water also acts as an important transport agent, so traces of these pollutants are found in surface water, wastewater, rainwater runoff, and urban sediments, sometimes far from their primary sources (Bika et al., 2022).

⁹ National Library of Medicine, National Toxicology Program, 2020. Developmental and Reproductive Toxicity Technical Report on the Prenatal Development Studies of Tris(chloropropyl) Phosphate (CASRN 13674-84-5) in Sprague Dawley Rats (Gavage Studies). DART Report, 2019. Web page. URL: https://ntp.niehs.nih.gov/sites/default/files/ntp/htdocs/dart/dart01_508.pdf?utm_source=chatgpt.com (accessed: 22.09.2025).

The ability of organophosphate esters (OPEs) to migrate long distances with air masses and ocean currents has been proven (Polyakova and Lebedev, 2019; Cristale et al., 2013). Several studies have demonstrated that OPEs can be transported from industrial emission sources to regions with minimal anthropogenic impact, including the Arctic¹⁰ and Antarctica (Fu et al., 2020; Na et al., 2020). Ten OPEs compounds were detected in seawater samples from the northwest Pacific and Arctic, with concentrations ranging from 8.5 to 143 ng/L, which is disproportionate. These levels are unexpectedly high for such areas located far from any pollution sources (Fu et al., 2020; Na et al., 2020; Xiao et al., 2021).

Pathways of OPEs entry into natural ecosystems

After release from consumer and construction materials, OPEs are distributed throughout all major environments (water, soil, air), subsequently accumulate in bottom sediments and dust, and enter the water and soil cycles. As a result, OPEs penetrate all ecosystems and form a ubiquitous background, ensuring their availability for uptake by biota and further transport through the food chain (Liu et al., 2019). The author's previous review presented systematized data on OPE levels in various natural ecosystem elements of several countries, allowing a quantitative estimation of the scale of their distribution and the ecological significance of this group of compounds' presence in natural environments (Bash, 2024). Once released into the environment, organophosphate flame retardants can be taken up by various plant species through their roots and/or leaves. Plants, in turn, make these compounds bioavailable to consumers, thereby enabling the entry of these pollutants into food chains (Lao et al., 2024). The environmental behavior of OPEs is primarily defined by the physicochemical properties of each specific compound, which subsequently determine their fate and, in particular, their availability for uptake by biota (Gbadamosi et al., 2021).

Uptake of OPEs by plants mainly occurs in two pathways: by roots (absorption through the soil or water solutions) and foliar uptake (via air and deposited particles). A number of field and laboratory experiments show that more hydrophilic compounds are more readily absorbed by plant root systems and are more actively involved in processes of migration in natural environments. In contrast, lipophilic OPEs tend to be retained on surfaces of leaves, in waxy fractions, and migrate to a limited extent. Each uptake pathway contribution is determined by a combination of factors, including the physicochemical properties of individual OPE compounds, as well as the characteristics of the plant itself and environmental conditions (Liu et al., 2019). In addition, each plant species has a specific "capacity" and ability to retain only a limited total OPEs amount, which is determined by the properties of the plant itself and also influenced by the physicochemical properties of the compounds involved (Lao et al., 2024).

Some plant species exhibit hyperaccumulation and exceptionally high concentrations of organophosphate esters (Lao et al., 2024). In particular, OPEs are frequently detected in edible plant tissues, including vegetables (such as lettuce, radish, cabbage, carrots, broccoli, onions, celery, tomatoes, cucumbers, and others), cereals (rice, wheat, etc.), and fruits (apples, oranges, pears, peaches, etc.) (Zhang et al., 2022). Consumption of these food products represents an important pathway of OPE exposure for humans (Lao et al., 2024). In addition, several studies have demonstrated that OPEs can undergo transformation through enzymatic metabolism in biota, as well as via other degradation pathways (microbial metabolism/biotransformation, base-catalyzed hydrolysis, and photodegradation), to, for example, potentially toxic organophosphorus diesters (OPDEs) (Li et al., 2019). Presented in water, OPEs can also be degraded into OPDEs during wastewater treatment processes or photolysis (Dowbysz et al., 2023). This suggests that degradation products of OPEs may coexist with their parent compounds in samples of various environmental matrices or food products (Gbadamosi et al., 2021). More importantly, several studies have reported that these degradation products may exhibit higher toxicity than the original triesters (Gbadamosi et al., 2021; Li et al., 2019).

Thus, organophosphate esters are characterized by persistence, toxicity of both the parent compounds and their metabolites, and the ability to bioaccumulate and biomagnify. Due to their lipophilic nature, OPEs accumulate to different degrees in various living organisms and can be effectively

¹⁰ Sagerup, K., Leonards, P., Routti, H., Fuglei, E., Aars, J., et al., 2011. Government pollution monitoring program. Organophosphorous flame retardants in Arctic biota. Web page. URL: <https://brage.npolar.no/npolarxmlui/bitstream/handle/11250/173195/OrganophosphorousFlameRetardants2011.pdf> (accessed: 12.09.2025)

transported along the food chain (Hou et al., 2023). As a result, organisms at all trophic levels are inevitably exposed to these compounds. Ultimately, such exposure can affect the reproduction and survival abilities of individual species, which leads to changes in community structure: some species displace others, the predator-prey balance is disrupted, and biodiversity can thus decline. This means that even at relatively low background concentrations in water or soil, the presence of OPEs disrupts the stability of ecosystems. Notably, these concentrations are comparable to, or in some cases exceed, those of traditional flame retardants, such as PBDEs, which are currently banned (Chen et al., 2021). The scientific community is also concerned by the fact that traces of OPEs are being detected in all corners of the planet, including remote and seemingly untouched regions. This ubiquitous nature of the contamination indicates that OPEs presence is not a local environmental issue but rather a global problem associated with risks to human health.

Pathways of human exposure

Organophosphate esters enter the human body mainly through the three pathways: dietary intake via trophic food chains, dermal contact, and inhalation of contaminated air or indoor dust. In addition, the maternal transfer of OPEs has been proven, through the placenta during pregnancy and subsequently through breast milk (Kim et al., 2014; Rojas et al., 2025; Sundkvist et al., 2010).

One of the most important sources of OPE intake by humans is food contaminated with these compounds. Comparative analysis of available studies indicates that almost all categories of food contain OPEs to some extent. Table 2 summarizes data on OPEs levels in various food products commonly found in the typical human diet. The selection of sources intentionally includes studies from different countries, demonstrating the ubiquity of OPEs and highlighting the scientific interest in this issue relevant for lots of national research communities.

It should be noted that one of the highest concentrations of OPEs compounds were detected in vegetables consisting of leaves (such as cabbage), with the higher OPEs concentrations in the leafy tissues of these plants comparing to the roots or stems. A similar pattern was observed for other leafy vegetables in the study region, including pakchoi cabbage, and Chinese chives, and related species (Zhang et al., 2022).

OPE concentrations in cereals varied by region and product type, the highest levels were reported in rice from China compared with other cereal samples (such as maize), as well as with potato samples (Zhang et al., 2022). Rice accounts for up to 60% of total food consumption in the study region and is an important food staple in East and Southeast Asian countries, so relatively high levels of OPE contamination in rice may pose a potential risk to consumers. Grain from industrial areas contains up to 800 ng/g of OPEs, as agricultural areas move away from industrial zones, the levels decrease to around 300 ng/g and reach minimum values for China in the regions of Sichuan, Hubei, and Guangxi (Zhang et al., 2022). Thus, the direct influence of industrial facilities' proximity on OPEs levels in environmental objects, particularly in cultivated plants, is evident. At the same time, the presence of even minimal OPE concentrations in areas remote from industrial facilities once again proves the existence of long-range transport of OPEs.

The study by Z. Lao et al. (2024) demonstrates the direct influence of the environment on the contaminant's composition entering living organisms and food products. Leafy and fruiting vegetables purchased at Shenyang (China) markets and in retail stores in Birmingham (United Kingdom) exhibited relatively high mean concentrations of OPEs (5.89–26.8 and 5.61 ng/g, respectively) and similar OPEs profiles were detected in air and dust samples collected at the same locations. Thus, these findings indicate that, in addition to contamination during the growing stage, food products may undergo further OPE contamination during their distribution and sale in indoor commercial places.

In addition to accumulation along food chains, where compounds bioaccumulate and OPE concentrations increase from plants to herbivores, predators, and then to humans, food products may also become contaminated with OPEs during production, industrial processing (for instance, during packaging, canning, and drying), and storage, due to their presence in packaging films, containers, and other materials in contact with food (Gbadamosi et al., 2021, Lao et al., 2024). For example, high levels of diphenyl(2-ethylhexyl)phosphate (EHDPP) were detected in most cereal, vegetable, and meat samples from Sweden, which was most likely associated with the use of EHDPP in food packaging materials (Gbadamosi et al., 2021). It has also been reported that cooking processes can reduce OPEs levels in food products (Li et al., 2019).

Table 2. Levels of organic phosphate esters presence in various food products with examples from a number of countries.

Sample type	OPEs levels	Study area	Target compounds and notes	Source
Vegetables (tomatoes, carrot, broccolis, onion, celery)	9.4–31.4 ng/g dry weight	Several regions of China, including agricultural and urban areas	Total OPEs, dominated by TEHP, TIBP, TEP, TnBP	Zhang et al., 2022
Cereals	8.08–802 ng/g dry weight		Total OPEs, with TCEP, TBOEP, TEHP, TnBP, and EHDPP as the predominant compounds	Zhang et al., 2022
Fruits (apples, bananas, oranges, pears, peaches, tangerines)	1.04–9.74 ng/g dry weight	China, Sweden, Australia	Total OPEs, predominantly chlorinated compounds, including TDCPP, TCPP и TCEP	Gbadamosi et al., 2021
Cabbage	Leaves: 2128 ng/g dry weight Roots: 554 ng/g dry weight	China, agricultural land, Dalian	Total OPEs, with the highest concentrations observed for TCPP	Lao et al., 2024
Vegetables	5.89–26.8 ng/g wet weight	China, markets in Shenyang	Total OPEs	Lao et al., 2024
Vegetables	5.61 ng/g wet weight	England, markets in Birmingham	Total OPEs	Lao et al., 2024
Fish	15000 ng/g lipid weight	Sweden	Total OPEs	Sundkvist et al., 2010
Fish	110–1900 ng/g lipid weight	Philippines, Manila Bay	Total OPEs including TCEP, TCPP, TDCPP	Kim et al., 2011
Meat (beef, chicken, turkey, lamb, goat, pork)	1.43–46.1 ng/g wet weight 3.95 ng/g wet weight	USA China	Total OPEs, with TBOEP accounting for 55.2–90.3% of the total OPE concentration in meat	Zhang et al., 2022
Dairy products (yogurt, milk, butter, cheese, milk powder)	0.60–71.4 ng/g wet weight	Belgium, Sweden, USA, China, Australia	Total OPEs	Zhang et al., 2022
Tap water	74–342 ng/l	Several cities of Korea	Total OPEs; TnBP, TCEP, TCPP, and TBOEP were detected in all samples	Wang et al., 2023
Tap water	3.1–940 ng/l			
Bottled water	up to 180 ng/l	China, The Pearl River Delta	Total OPEs	Wang et al., 2023
Barreled water	11–100 ng/l			

OPEs are also widely present in water, and their levels vary significantly between different cities. In some cases, relatively high levels have been reported (Table 2). The potential risks posed by drinking water to human health depend on the raw water source and the treatment process used (Wang et al., 2023). OPE concentrations in drinking water are significantly affected by economic development and population density. It has been shown that OPE levels in drinking water have the specific tendency to decrease from industrial cities to less industrialized ones, as well as from coastal cities (average value of 154 ng/L) to cities in inland regions (119 ng/L). In surface water, these compounds are detected at concentrations of 25–3 671 ng/L, in drinking water – 4–719 ng/L, and in wastewater – 104–29 800 ng/L (Wang et al., 2023).

The highest OPE concentrations for China tap water were detected in the large industrial cities of Ulsan (mean value 144 ng/L) and Ansan (74 ng/L). However, in several coastal cities with developed industry (Shanghai and Dalian), the lowest concentrations for the studied region were observed (Wang et al., 2023). Such differences in OPE levels may be explained by the use of advanced water treatment technologies. When drinking water from different types of containers was analyzed, the mean total OPEs content decreased in the following order: tap water > bottled water > barreled water. For human safety, it is very important to develop water treatment technologies capable of removing all types of contaminants and, at the same time, to regularly monitor raw water sources (Wang et al., 2023).

Humans spend most of their time indoors: at home, at school, in offices, at workplaces, and so on. OPEs are typically used in the production of items that fill these indoor spaces, as well as in materials used in most vehicle interiors, so exposure to flame retardants is ultimately inevitable. These compounds enter the environment from construction materials, everyday household plastic items, textiles, and paint coatings – from everything that permanently surrounds humans in daily life. Table 3 presents average values of OPE levels entering the human body from the environment through different exposure pathways.

The relative contribution of each pathway to overall exposure depends, among other factors, on the physicochemical properties and commercial use of specific compounds. In addition, analysis of data on different pathways of OPE intake shows pronounced geographical differences: exposure levels vary between countries and between regions within a single country. This is associated with a combination of factors: the regulatory framework for OPEs in a particular country, the nature and capacity of regional industries, water treatment and waste management methods used, etc.

Differences in dietary intake of OPEs also directly depend on the characteristics of the basic diet and the food preferences of local residents. Thus, a difference is observed between global average estimates (as presented in the meta-analysis by Gbadamosi et al., 2021) and the exposure levels received by adults in Europe (using Norway and Sweden as examples) and in China. Lifestyle factors (occupation and age) also influence other pathways of OPE exposure. According to the study of Y. Dang et al. (2023), OPE levels in the urine of adults were higher than those measured in infants, and levels detected in firefighters' urine were higher than the average levels observed in ordinary people.

An important and alarming conclusion has been made regarding the impact of commonly used OPEs on children. This population group is particularly vulnerable due to frequent hand-to-mouth behavior, as confirmed by epidemiological and analytical studies (Rojas et al., 2025). Even under the same environmental background conditions compared with adults, children breathe more frequently, consume more food and water per body weight, and ingest larger amounts of dust (the main carrier of OPEs indoors). As a result, the OPE doses received per kg of body weight are higher in toddlers than in adults. At the same time, the developing nervous system of children is more sensitive to any exposure. According to an evaluation of data from the U.S. National Health and Nutrition Examination Survey (NHANES) for 2013–2018, the risk of behavioral and cognitive disorders is higher for children than for adults (Rojas et al., 2025).

Moreover, 6 new OPEs and elevated levels of bis(2-ethylhexyl)phenyl phosphate (BEHPP) were detected in paired samples of chorionic villi and placenta, indicating maternal transfer of these contaminants (Li et al., 2024). In addition to maternal transfer during the perinatal period, infants receive small doses of OPEs through breast milk (Kim et al., 2014; Rojas et al., 2025).

Table 3. Human exposure to OPEs depending on their pathways of entry from the environment

Exposure pathway	Age group	Mean values of obtained exposure (daily intake values), ng/kg of body weight per day			Source
		Cl-OPE	Alkyl OPE	Aryl OPE	
Air, inhalation	Adults	24.73	2.58	1.12	
	Toddlers	2.23	1.23	0.30	
Dust, inhalation	Adultse	14.56	2.97	1.29	Gbadamosi et al., 2021
	Toddlers	10.30	23.21	5.28	
Dermal uptake	Adults	24.36	3.63	25.64	
	Toddlers	532.00	2.73	628.00	
Ingestion	Adults		55.00		Ding et al., 2018
			Sweden, Norway: average values: 86.0		
Ingestion	Adults	65.4	64.21	39.80	Gbadamosi et al., 2021
	Children	18.92	66.03	4.59	Ding et al., 2018
Water ingestion			97.70		Wang et al., 2023
		North America: 0.02–1.3 on average for cities; 1.2–9.7 in areas with high loads and proximity to OPE sources			Kim and Kannan, 2018
Water ingestion	Adults	3.16	1.05	0	Gbadamosi et al., 2021
		Korea: average values 1.80–11.80			
Ingestion with breast milk	Toddlers	0.87	0.51	0	Gbadamosi et al., 2021
		73.7	248.10	19.63	
Ingestion with breast milk	Infants		Vietnam: average values 10 ng/kg lipid weight		Kim et al., 2014
			Japan: average values 22 ng/kg lipid weight		
Total value	Adults	132.2	83.43	67.8	Gbadamosi et al., 2021
	Children	564.00	93.67	638.00	

Toxic effects of OPEs

As OPEs became increasingly common in consumer products, there has been a need for toxicological and environmental studies to determine the impact of these additives on humans and the environment (Tudor, 2022). OPEs are currently classified as endocrine-disrupting compounds that interfere with normal hormonal development and exhibit carcinogenic and neurotoxic properties (Rojas et al., 2025; Zhang et al., 2024). A key concern is that the metabolic transformation of OPEs is often associated with increased toxicity and more pronounced endocrine-disrupting effects, raising concerns about long-term and delayed health risks (Pyambri et al., 2025).

It is important to remember that the release of OPEs into natural ecosystems increases the toxic burden, since 'legacy' flame retardants – PBDEs, are still present in ecosystems. These compounds are characterized by high lipophilicity, a tendency to bioaccumulate in fatty tissues, and the ability to cause adverse effects in both animals and humans (Kristanti et al., 2023). Understanding the mechanisms of these compounds and their metabolites to harm the global ecosystem and human health is critically important for informing industry and driving legislative changes. Addressing the problem of 'regrettable substitutions', where one group of hazardous anthropogenic compounds (in this case, PBDEs) is replaced by another, equally hazardous one, may help to mitigate long-term impacts on the environment and human health (Rojas et al., 2025).

Table 4 presents the summarized data on the toxic effects of OPEs group compounds, obtained in model organisms and cellular systems as well as information on identified effects on humans.

It should be noted that endocrine disruption and neurotoxicity were observed at submicromolar concentrations, suggesting the particular sensitivity of some biological systems to OPEs exposure. The use of modern analytical methods has shown that even at subtoxic concentrations, significant changes in gene expression occur. Thus, molecular changes take place at low doses of OPEs even in the absence of detectable effects on cell viability and phenotype (Pyambri et al., 2025).

Overall, exposure of rodents to TCEP, TnBP, TBEP, TDCP, TPP or TCPP during pregnancy did not result in adverse effects on the fetus or newborn animals. However, continuous exposure to TCEP for two generations of mice reduced the number of live-born males in the third generation. A similar study with TnBP in rats showed that pups born to exposed rats had lower body weights in the first weeks of life than pups born to control rats. Studies in rats and mice also demonstrated that exposure to TCP before and during pregnancy may increase the number of stillborn pups¹¹.

It should be noted that current understanding of the mechanisms of OPEs' impacts on living organisms and humans is only beginning to develop due to the relative novelty of this issue. The mechanisms and principles of OPEs' influence at the level of the ecosystem also remain insufficiently studied. Most available data were obtained from a relatively limited number of model experiments. Especially noticeable gaps exist in the understanding of the combined effects of OPEs on components of natural ecosystems, where toxic PBDEs are still present, as well as their distribution patterns, accumulation in living organisms, and long-term delayed effects.

¹¹ Agency for Toxic Substances and Disease Registry (ATSDR), 2012. Toxicological profile for phosphate ester flame retardants. Web page. URL: <https://www.atsdr.cdc.gov/toxprofiles/tp202.pdf> (accessed: 20.09.2025).

Table 4. Key adverse effects of individual organophosphorus ester compounds.

Compound name	Influence on animals	Toxic effects on humans	Source
TnBP	Causes urinary bladder damage in rats when administered for 10 weeks or longer Memory impairment in mice	Neurotoxicity	ATSDR ¹¹ Dou and Wang, 2023
TBEP	Disruption of the blood-brain barrier in rats Reproductive and ontogenetic toxicity Suppresses cell viability Developmental toxicity – effects on the brain during early development Behavioral changes (affecting reproduction and the ability to get food) in rats	Elevated TCEP concentrations in school dust and particulate matter correlate with decreased cognitive abilities in children Weak association between perinatal exposure to flame retardants and cognitive impairment, with only a moderate positive association observed with intelligence level Behavioral changes (in combination with other OPEs)	Dou and Wang, 2023 Rojas et al., 2025 ATSDR ¹¹ Blum et al., 2019 Dou and Wang, 2023
TCEP	Reduced fertility in mice when exposed for 18 weeks prior to mating Memory impairment in mice Neurotoxicity; endocrine disruption; genotoxicity	Risk of carcinogenicity and disruption of the reproductive system in young children	Rojas et al., 2025 Wang et al., 2020
TDCPP	Differences in anxiety levels in mice, depending on sex and diet; Increased anxiety behavior in adult female zebrafish (danio-erio)	Maternal transfer to the child is associated with decreased verbal memory and cognitive impairment in children, depending on gender Decreased intelligence levels and memory impairment have been found in children exposed to flame retardant during the prenatal period Urinary concentrations have been associated with decreased cognitive function in elderly individuals Declared as a carcinogenic	Blum et al., 2019 Proposition 65 ¹² Pyambri et al., 2025 Rojas et al., 2025
	Neurotoxicity, endocrine disruption. Carcinogenicity (regulatorily recognized). Tendency to accumulate in brain tissue. Pronounced impact on intestinal microbiota – a model experiment demonstrated the strongest intestinal toxicity compared to TCEP and TCPP. Ability to accumulate in the nervous system		

Compound name	Influence on animals	Toxic effects on humans	Source
Triphenylphosphate (TPP)	Increased anxiety behavior in adult male mice and zebrafish	Maternal transfer to the child is associated with the IQ decline, as well as working memory and cognitive disruption in children depending on gender	Rojas et al., 2025
	Differences in anxiety levels in mice depending on sex and diet		
EHDPP, TBPP – tris(2-biphenyl) phosphate	Memory and attention impairments in rats	Significant endocrine disrupting effects	Dou and Wang, 2023 Wang et al., 2020 Zhang et al., 2024
	Developmental defects and swimming abnormalities in zebrafish embryos/larvae at concentrations of 10^{-7} M or higher		
	Effects on reproductive behavior in zebrafish		
TPHP	Neurotoxicity; cardiotoxicity; and hepatotoxicity. At higher concentrations – inflammation and significant cellular damage occur; in the liver, functional parameters are reduced at $\geq 25 \mu\text{M}$	Suppression of cell viability; developmental toxicity; neurotoxicity; cardiotoxicity and hepatotoxicity; contact allergic effects; immunotoxicity	Blum et al., 2019 Dou and Wang, 2023
	A decrease in intelligence levels and impaired memory were identified in children exposed to flame retardants during the prenatal period		

Conclusion

OPEs presence in natural ecosystems is attracting increasing attention from the scientific community worldwide. They can enter the environment from various points and diffuse sources, persist for long periods, and contaminate soil, water, and the atmosphere, exhibiting persistence, high toxicity, and the ability to bioaccumulate and biomagnify. Thus, organophosphate esters do pose a threat to ecosystem sustainability and can be regarded as a regrettable substitute for PBDEs.

Although until recently the aspiration was considered the main route of OPEs entry into the human body, recent studies indicate that plants can absorb and metabolize OPEs from the environment, thereby playing an important role at the initial stage of their transmission through the food chain. The trophic transfer of OPEs is a key to understanding the overall level of pollution and the hazardous impact of these flame retardants on the human body. Even at relatively low background levels in the environment, consistent transfer through the food chain leads to increasing concentrations and accumulation of OPEs in organisms at higher trophic levels. Considering the continuous emission of OPEs from polymer-containing materials and their presence in food of both plant and animal origin, humans, as the top consumer, are the recipients of the highest concentrations of this toxic substance.

Since OPEs have been detected in many agricultural crops, Russia, with its rich, fertile lands and actively developing agricultural sector, is vulnerable. Furthermore, the country exports products from China, the world's largest producer of goods, where OPE are widely used. At the same time, OPEs levels in agricultural products and consumer goods in this country are not assessed.

Particular attention should also be paid to the investigation of the long-term effects of these compounds. An assessment of environmentally significant concentrations is necessary for more accurate prediction of health threats and environmental risks. It is evident that the flame retardant market still requires an environmentally friendly, modern alternative, and the search for adequate replacements for outdated PBDEs and OPEs may also become a focus of contemporary Russian research. The material presented in this review may serve as a starting point for planning further scientific studies on hazardous compounds in the conditions of Russian ecosystems, with subsequent integration of the results into global databases.

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