

Review on Degradation Behavior and Transformation Products of Organophosphorus Flame Retardants

Lan Jiang, Yue Shi, Yuyao Zhou, Yonghao Huangfu, Siyang Xu and Qingwei Bu *

School of Chemical & Environmental Engineering, China University of Mining & Technology-Beijing, Beijing 100083, China

* Correspondence: qingwei.bu@cumtb.edu.cn; Tel./Fax: +86-10-62339298

How To Cite: Jiang, L.; Shi, Y.; Zhou, Y.; et al. Review on Degradation Behavior and Transformation Products of Organophosphorus Flame Retardants. *Glob. Environ. Sci.* **2026**, 2(3), 404–425. <https://doi.org/10.53941/ges.2026.100026>

Publication History

Received: 6 March 2026

Revised: 22 August 2026

Accepted: 1 September 2026

Published: 28 September 2026

Keywords

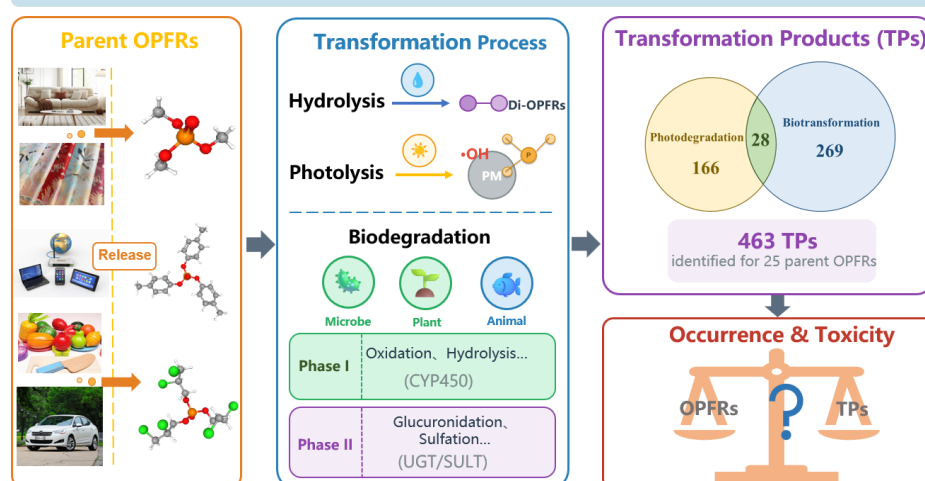
organophosphorus flame retardants;
transformation pathways;
transformation products;
toxicological effects

Highlights

- 463 transformation products from 25 parent OPFRs were compiled
- Hydrolysis and hydroxylation dominate OPFR biotransformation pathways
- 19 TPs were confirmed in multiple environmental matrices
- Some diester and hydroxylated TPs show stronger toxicity than parent OPFRs

Abstract: Organophosphorus flame retardants (OPFRs), as widespread alternatives to brominated flame retardants, are now ubiquitous in the environment and generate a large number of uncharacterized transformation products (TPs) through abiotic and biotic transformation. However, a comprehensive description of OPFR TPs is still lacking. This review systematically integrates current knowledge on the environmental fate of OPFRs, focusing on the formation, occurrence, and toxicity of TPs. We compiled 463 TPs derived from 25 parent OPFRs identified in laboratory studies, involving 1338 reaction pathways, among which hydrolysis (>29%) and hydroxylation (>30%) were the dominant reaction pathways in microbial, plant, and animal metabolism. To date, 19 TPs have been confirmed in multiple environmental matrices, among which diester metabolites (e.g., diphenyl phosphate (DHP) and bis(1,3-dichloro-2-propyl) phosphate (BDCIPP)) are most frequently detected in human urine, blood, and breast milk. Importantly, accumulating toxicological data indicate that TPs such as hydroxylated triphenyl phosphate (OH-TPHP), BDCIPP, and di-n-butyl phosphate (DnBP) exhibit greater endocrine-disrupting, developmental, and metabolic toxicity than their parent compounds. Given the evidence presented, heightened emphasis should be placed on incorporating TPs into environmental risk assessment.

Degradation Behavior and Transformation Products of Organophosphorus Flame Retardants



1. Introduction

Organophosphorus flame retardants (OPFRs), as key alternatives to brominated flame retardants, have seen

widespread adoption across plastics, electronics, textiles, furniture, and other sectors, becoming mainstream flame retardants on the market [1,2]. By 2021, 56 types of OPFRs

had entered global production and sales. China's annual consumption of OPFRs increased from 100,000 tons in 2011 to 598,000 tons in 2020 [3,4]. Based on the type of substituent, OPFRs are typically classified into halogenated alkyl-type (Cl-OPFRs), non-halogenated alkyl-type (Alkyl-OPFRs), and aryl-type organic phosphorus flame retardants (Aryl-OPFRs) [5]. The physicochemical parameters of selected OPFRs are listed in Table 1.

OPFRs are typically incorporated into products across various industries through physical addition

rather than chemical bonding, with mixing ratios exceeding 10% (w/w) in some polyurethane foam products [6]. Consequently, during product manufacturing, transportation, use, and disposal, OPFRs readily migrate into the environment via pathways such as abrasion, leaching, volatilization, permeation, and dissolution [7]. To date, OPFRs have been detected in air [8], dust [9], surface water [10], groundwater [11], rainwater [12], sediments [13], soil [14], plants [15], aquatic animals [16] and even human tissues such as blood [17], hair [18] and nails [19].

Table 1. Chemical information and physicochemical parameters of selected OPFRs.

Compound	Abbreviation	CAS Number	Molecular Formula	Mw	LogKow ¹	Vapor Pressure at 25 °C (mmHg) ¹
Alkyl-OPFRs						
Triethyl phosphate	TEP	78-40-0	C ₆ H ₁₅ O ₄ P	182.15	0.87	0.153
Trimethyl phosphate	TMP	512-56-1	C ₃ H ₉ O ₄ P	140.07	-0.60	0.379
Tripropyl phosphate	TPP	513-08-6	C ₉ H ₂₁ O ₄ P	224.23	2.35	0.023
Triisopropyl phosphate	TIPP	513-02-0	C ₉ H ₂₁ O ₄ P	224.23	2.12	0.128
Tributyl phosphate	TnBP	126-73-8	C ₁₂ H ₂₇ O ₄ P	266.31	3.82	3.49 × 10 ⁻³
Triisobutyl phosphate	TiBP	126-71-6	C ₁₂ H ₂₇ O ₄ P	266.31	3.60	1.29 × 10 ⁻²
Tris(2-ethylhexyl) phosphate	TEHP	78-42-2	C ₂₄ H ₅₁ O ₄ P	434.63	9.49	* 1.58 × 10 ⁻⁷
Tris(2-butoxyethyl) phosphate	TBOEP	78-51-3	C ₁₈ H ₃₉ O ₇ P	398.47	3.00	* 3.68 × 10 ⁻⁷
Cl-OPFRs						
Tris(2-chloroethyl) phosphate	TCEP	115-96-8	C ₆ H ₁₂ Cl ₃ O ₄ P	285.49	1.63	* 3.60 × 10 ⁻⁴
Tris(3-chloropropyl) phosphate	TCPP	26248-87-3	C ₉ H ₁₈ Cl ₃ O ₄ P	327.57	3.11	4.79 × 10 ⁻⁶
Tris(1-chloro-2-propyl) phosphate	TCIPP	13674-84-5	C ₉ H ₁₈ Cl ₃ O ₄ P	327.57	2.89	* 2.63 × 10 ⁻⁴
Tris(2,3-dichloropropyl) phosphate	TDCPP	78-43-3	C ₉ H ₁₅ Cl ₆ O ₄ P	430.9	3.65	2.28 × 10 ⁻⁷
Tris(1,3-dichloro-2-propyl) phosphate	TDCIPP	13674-87-8	C ₉ H ₁₅ Cl ₆ O ₄ P	430.9	3.65	* 3.08 × 10 ⁻⁶
Tetrakis(2-chloroethyl) dichloroisopentyl diphosphate	V6	38051-10-4	C ₁₃ H ₂₄ Cl ₆ O ₈ P ₂	582.99	3.31	2.06 × 10 ⁻⁸
Aryl-OPFRs						
Tri(p-cresyl) phosphate	TpCP	78-32-0	C ₂₁ H ₂₁ O ₄ P	368.36	6.34	* 8.25 × 10 ⁻⁸
Tri(m-cresyl) phosphate	TmCP	563-04-2	C ₂₁ H ₂₁ O ₄ P	368.36	6.34	* 1.58 × 10 ⁻⁷
Tri(o-cresyl) phosphate	ToCP	78-30-8	C ₂₁ H ₂₁ O ₄ P	368.36	6.34	* 3.83 × 10 ⁻⁷
Triphenyl phosphate	TPHP	115-86-6	C ₁₈ H ₁₅ O ₄ P	326.28	4.70	* 2.03 × 10 ⁻⁶
Triphenylphosphine oxide	TPPO	791-28-6	C ₁₈ H ₁₅ O ₂ P	278.28	2.87	2.82 × 10 ⁻⁷
Diocetyl phenylphosphonate	DOPP	1754-47-8	C ₂₂ H ₃₉ O ₃ P	382.52	7.51	1.52 × 10 ⁻⁷
Cresyl diphenyl phosphate	CDP	26444-49-5	C ₁₉ H ₁₇ O ₄ P	340.31	5.25	1.07 × 10 ⁻⁷
Resorcinol bis(diphenyl phosphate)	RDP	57583-54-7	C ₃₀ H ₂₄ O ₈ P ₂	574.45	7.41	2.06 × 10 ⁻⁸
Bisphenol A bis(diphenyl phosphate)	BDP	5945-33-5	C ₃₉ H ₃₄ O ₈ P ₂	692.64	-	-
2-ethylhexyl diphenyl phosphate	EHDP	1241-94-7	C ₂₀ H ₂₇ O ₄ P	362.4	6.3	* 6.68 × 10 ⁻⁷
Bis(2-ethylhexyl) phenyl phosphate	BEHPP	16368-97-1	C ₂₂ H ₃₉ O ₄ P	398.26	7.89	1.7 × 10 ⁻⁷
Biphenyl diphenyl phosphate	BPDPP	132-29-6	C ₂₄ H ₁₉ O ₄ P	402.10	6.46	2.06 × 10 ⁻⁸
Tris([1,1'-biphenyl]-2-yl) phosphate	TBPHP	132-28-5	C ₃₆ H ₂₇ O ₄ P	554.16	9.99	2.06 × 10 ⁻⁸
Naphthyl diphenyl phosphate	NPHP	18872-49-6	C ₂₂ H ₁₇ O ₄ P	376.09	-	-
Isodecyl diphenyl phosphate	IDDP	29761-21-5	C ₂₂ H ₃₁ O ₄ P	390.5	7.3	4.72 × 10 ⁻⁸

¹ Data sourced from calculations using EPIWeb 4.1. * Data sourced from Sandra Brommer, et al. [20].

Extensive toxicological studies have confirmed that OPFRs exert various adverse effects on living organisms, including cardiotoxicity [21], neurotoxicity [22], endocrine disruption [23], reproductive and developmental toxicity [24], visual impairment induction [25] and carcinogenicity [26,27]. Due to their potential hazards to human health, the use of several relevant OPFRs has been restricted by international regulations. For example, several U.S. states have proposed legislation to restrict the use of such substances in children's products and upholstered furniture [28].

Transformation products of OPFRs, encompassing diverse metabolites and breakdown products, arise from the biotic and abiotic degradation (e.g., hydrolysis, photolysis, and microbial degradation) of their parent compounds. TPs, both within the environment [29] and biological systems [30], are garnering attention, as some TPs exhibit toxicities comparable to or exceeding those of parent OPFRs [31].

While there are already reviews that provide a systematic summary of the environmental fate of OPFRs, insufficient attention has been paid to their TPs. Tian et al. [32] and Zhang et al. [33] summarized the occurrence,

migration, and transformation mechanisms of OPFRs in soil; Zhou et al. [34] and Yang et al. [35] focused on the removal technologies and influencing factors of OPFRs in soil and water; Yao et al. [7] discussed the bioaccumulation and metabolic processes of OPFRs. However, existing reviews have rarely addressed the occurrence and related risks of OPFR TPs. Therefore, this review systematically examines the formation, environmental occurrence, and toxic effects of OPFR TPs, to further advance our understanding of OPFR degradation and transformation mechanisms and support the ongoing risk assessment of these emerging contaminants.

2. Materials and Methods

2.1. Search Strategy and Eligibility Criteria

To minimize selection bias and enhance reproducibility typically lacking in traditional narrative reviews, this study utilized an adapted literature retrieval process based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A

comprehensive literature search was conducted across Web of Science and Scopus, from database inception to 31 May 2026. Topic Search (TS) = (“Organophosphorus flame retardants” or “organophosphate esters” or “OPFRs” or “OPEs”) AND TS = (“metabolite” or “degradation” or “transformation product” or “hydrolysis” or “biodegradation” or “photodegradation” or “toxicity” or “environment occurrence” or “non-targeted identification”). Studies were included if they met the following criteria: (1) peer-reviewed publications written in English; (2) studies specifically investigating the kinetics, pathways or TPs of OPFRs hydrolysis, photolysis or biodegradation; (3) the toxicological effects of OPFR TPs. Literature about OPFRs degradation by advanced oxidation processes (AOPs) was excluded (n = 37), as AOPs are merely laboratory-based technologies with inconsistent experimental conditions and coverage of few OPFR species. The detailed article screening and selection process is illustrated in the adapted PRISMA flow diagram (Figure 1).

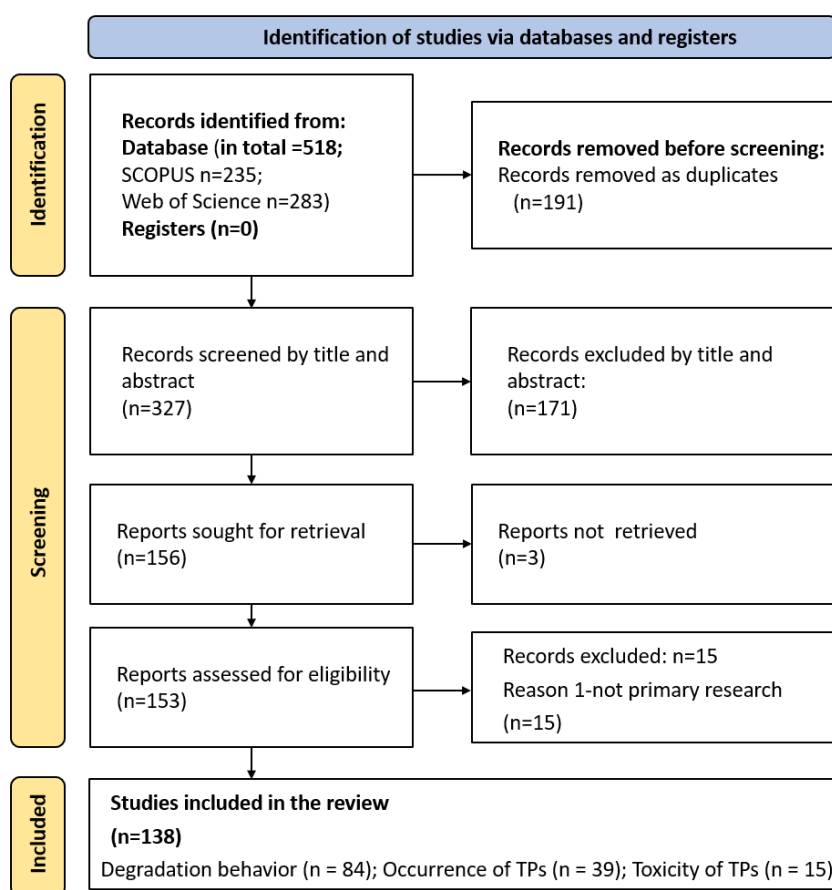


Figure 1. PRISMA flow diagram of the literature screening and selection process.

2.2. Selection Process and Data Collection Process

Based on the initial search, we identified 518 records on the degradation behavior and TPs of OPFRs. After importing all references into NoteExpress v4.3.0, 191 duplicated records were removed. A two-step screening

process was then adopted to select the required articles. First, articles were reviewed based on their titles and abstracts, and 171 records that did not meet the inclusion criteria were excluded. Second, the remaining 156 articles were further examined based on full texts; of these, 3 could not be retrieved and an additional 15 were excluded

as they were not primary research. Two reviewers independently screened all studies to determine the final list. Eventually, 138 articles were included in this review.

As this review focuses on the degradation behaviors, transformation pathways, environmental occurrence and toxic risks of OPFRs and their TPs, we extracted the following information from each included study: (1) basic study information, including research themes determined by topic keywords, research media classified according to experimental matrix, and study types (laboratory simulation, field monitoring, epidemiological investigation); (2) transformation process data, including experimental conditions (e.g., pH, temperature, microbial strains/plants/animals), reaction kinetics (rate constants, half-lives), identified transformation pathways, and the chemical structures of TPs. Only TPs identified by chromatography-coupled tandem mass spectrometry (MS/MS) were collected, excluding those predicted by computational models. (3) environmental occurrence of TPs, including concentrations and detection frequencies of TPs in various environmental matrices (e.g., human

urine/blood, breast milk, food, air, dust, surface water, soil); (4) toxicological effects, including experimental models (*in vitro*, *in vivo*, or epidemiological), exposure regimens, toxicity endpoints.

3. The Transformation Process of Organophosphorus Flame Retardants

3.1. Hydrolysis

Given the core ester structure of OPFRs, hydrolysis represents a key pathway for their natural transformation. The hydrolysis reaction of OPFRs is an S_N2 nucleophilic substitution process [36,37], as shown in Figure 2. Under acidic or neutral conditions, the nucleophilic group H_2O attacks the positively charged carbon (C) atom, with the O-Me bond breaking preferentially. Under basic conditions, the nucleophilic group OH^- or H_2O attacks the centrally positioned, positively charged phosphorus (P) atom, with the P-OMe bond breaking. Since OH^- exhibits significantly higher nucleophilicity than H_2O , hydrolysis primarily occurs at the P atom [36].

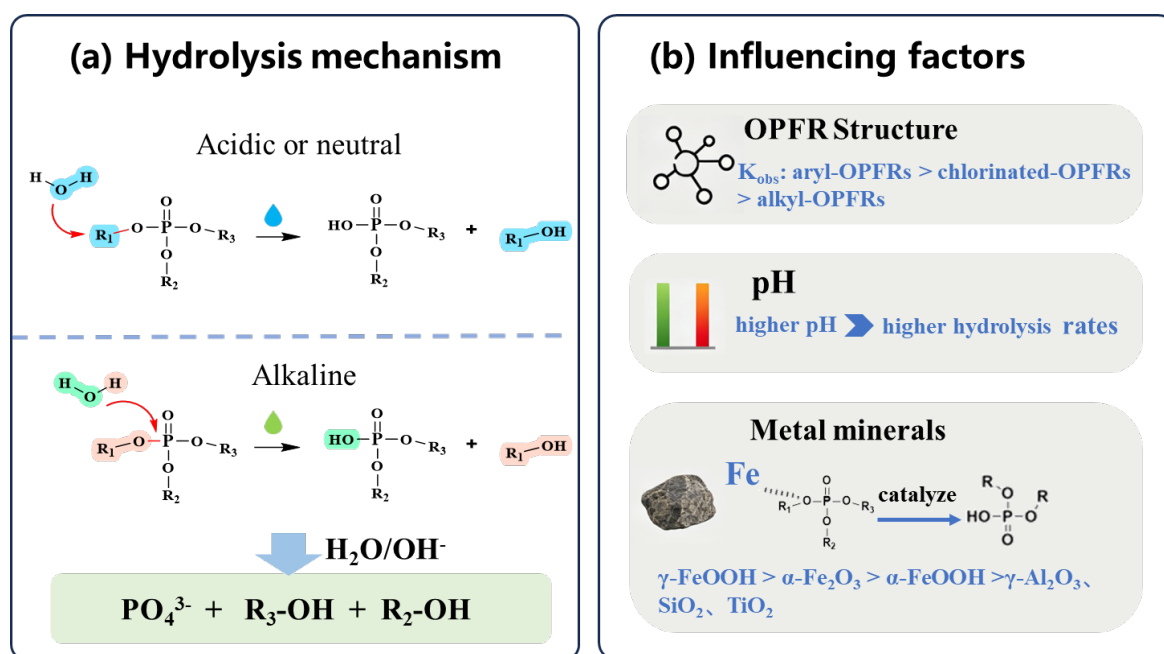


Figure 2. Hydrolysis mechanisms and influencing factors of OPFRs. (a) Hydrolysis mechanisms under acidic/neutral and alkaline conditions; (b) Key factors affecting OPFR hydrolysis.

In aqueous buffer systems, the hydrolysis of most OPFRs only occurs significantly under alkaline conditions (pH 9–12). The half-lives of eight common OPFRs (including TDCPP and TCEP) ranged from 0.02 to 170 days at pH 9–12 [38]. Their hydrolysis rates increased linearly with rising solution pH. However, under neutral pH conditions, the half-lives of all OPFRs except TCEP exceeded two years.

Different types of substituent and spatial structure result in systematic variations in hydrolytic activity, with rates generally following the order aryl-OPFRs > chlorinated-OPFRs > alkyl-OPFRs. Hydrolytic rates are

negatively correlated with the acid dissociation constant (pK_a) of the corresponding alcohol leaving group. The hydrolysis rate of alkyl OPFRs decreases with increasing side-chain length. The ortho-substituted tri-o-cresyl phosphate (ToCP) isomer has a slightly higher hydrolysis rate than the meta- and para-isomers [39]. Table S3 summarizes the hydrolysis rate $K_{obs}(t_{1/2})$ of several known OPFRs in near-neutral solutions, with half-lives ranging from a minimum of 7.5 days to over a thousand years. This suggests that, without catalysts, non-biological hydrolysis contributes negligibly to the degradation of most OPFRs in natural aquatic environments.

Many transition metal ions and mineral surfaces can catalyze the hydrolysis process of OPFRs. Sodium perborate (NaBO_3) dissociates to produce the nucleophilic reagent HOO^- , which can increase the hydrolysis rates of aromatic OPFRs, such as TpCP and TPHP by 10 to 100 times, with half-lives in aqueous solutions ranging from 4 to 90 min [40]. Natural minerals can accelerate the hydrolysis rate of OPFRs; at pH = 6, the hydrolysis half-life of most OPFRs is reduced to <10 days [41]. Li et al. [42] synthesized $\alpha\text{-MnO}_2$ nanorods that could completely hydrolyze pNPP (a model compound of organophosphate esters) within 50 h under the conditions of pH 5.0 and 25 °C. They first revealed the mineral's catalytic mechanism by integrating in situ spectroscopy with theoretical calculations: (a) Lewis acid sites on crystal planes induce significant electron redistribution in pNPP, enhancing the electrophilicity of phosphorus atoms and making them more susceptible to nucleophilic attack; (b) Coordination reactions between the mineral surface and ester functional groups weaken the bond between the ester and the central phosphorus atom, promoting the dissociation of the leaving group. Therefore, the Lewis acid strength on the mineral surface and the coordination ability of metal ions dominate the catalytic effect of minerals on OPFRs. Fe(III) (hydr)oxides exhibit higher catalytic activity for OPFRs hydrolysis than Al-, Si- and Ti-based oxides [41]. Additionally, reducing sulfur compounds such as HS^- and polysulfides can participate in the nucleophilic substitution reactions of certain Cl-OPFRs. By attacking the α -carbon atom, they accelerate ester bond cleavage and exhibit higher reactivity than OH^- -mediated basic hydrolysis [43,44].

Most current studies on the hydrolysis of OPFRs [38,41,45] indicate that diester phosphates are the main detected degradation products, and further hydrolysis of diester phosphates is generally slow and limited under environmentally relevant conditions. Their hydrolytic stability is higher than that of the parent OPFRs and deserves more attention in future research.

3.2. Photolysis

Current research on the photolysis of OPFRs has focused on atmospheric and aquatic environments; this section discusses the photolysis behavior of OPFRs in these two environmental media separately.

3.2.1. Photolysis of OPFRs in the Atmosphere

Among the most potent oxidative species in the atmosphere, hydroxyl radicals ($\cdot\text{OH}$) serve as the primary driving force for the photolysis of OPFRs. There are three pathways for the photolysis reaction between OPFRs and $\cdot\text{OH}$ (Figure 3a): (i) $\cdot\text{OH}$ radical addition to substituents bonded to the phosphorus center; (ii) $\cdot\text{OH}$ radical addition to the phosphorus center, yielding phenols or alcohols; (iii) hydrogen abstraction reactions

with atmospheric O_2 to form peroxides, ultimately generating highly reactive, low-molecular-weight carbonyl products [46]. The dominant transformation pathways may differ among OPFRs with different substituent groups. Yu et al. [47] combined quantum chemical calculations and master equation kinetics, and discovered that $\cdot\text{OH}$ addition to the benzene ring to form the hydroxylated triphenyl phosphate (OH-TPHP) adduct, followed by reaction with O_2 to produce phenolic phosphate esters, is the energetically most favorable pathway for the reaction between TPHP and $\cdot\text{OH}$. In contrast, Li et al. [48,49] calculated the atmospheric oxidation mechanism of TCPP and TpCP initiated by $\cdot\text{OH}$ radicals using density functional theory (DFT). They found that hydrogen abstraction has lower reaction energy barriers and activation free energies than $\cdot\text{OH}$ addition, and thus is the dominant reaction pathway.

The photolysis kinetics of OPFRs in the atmosphere are mainly regulated by molecular structure. Figure 3b and Table S4 summarize the atmospheric kinetic parameters of several OPFRs, with second-order rate constants ($k(\cdot\text{OH})$) generally ranging from 10^{-12} – 10^{-10} $\text{cm}^3 \text{ molecule}^{-1} \text{ s}^{-1}$. Under global average atmospheric $\cdot\text{OH}$ concentrations, their half-lives span 1.7 h to 14 days. Water molecules in the atmosphere inhibit the reaction between gaseous TCPP and $\cdot\text{OH}$ [48]. Through hydrogen bonding, water molecules stabilize the precursor complex and transition state, thereby increasing the activation free energy of the hydrogen extraction reaction and reducing the reaction rate. This extends the lifetime from 1.7 h to 0.5–20.2 days.

Some OPFRs (e.g., TpCP, TBOEP, TPHP) tend to partition onto atmospheric particles because of their low vapor pressure and typical characteristics as semi-volatile organic compounds (SVOCs). The heterogeneous oxidation reaction of OPFRs is relatively more complex, and the size of the particles, the gas-particle distribution and the state of the gas mixture would affect the heterogeneous oxidation reaction of OPFRs [50]. Lao et al. [51] found that the photodegradation rates of TBOEP in particulate matter decreased with increasing particle size within the 1 μm range. This may be attributed to the reactivity of particulate organic matter under $\cdot\text{OH}$ exposure being significantly influenced by its surface area to volume ratio (SA/V). Air relative humidity (RH) is crucial for the heterogeneous photolysis of OPFRs. Under high humidity, particles behave more like liquids with lower viscosity, which enhances the diffusion of $\cdot\text{OH}$ inside the particles and accelerates the reaction rate. When RH increases from 35% to 68%, the reaction rate of TBOEP can be enhanced by 19% [52]. When humidity rose from 45% to 68%, the 72-h photodegradation rate of TPHP rises from 29.1% to 50.9% [53]. Transition metals in atmospheric particles can catalyze the transformation of OPFRs via Fenton-like reactions. For instance, Fe^{2+} can increase the reaction rates of tricresyl phosphate (TCP) and TBOEP by over 50% [52]. Another

study [53] also reported that MnSO_4 , CuSO_4 , FeSO_4 and $\text{Fe}_2(\text{SO}_4)_3$ in the atmosphere exert a slight catalytic effect on the heterogeneous photodegradation of TPHP. CuSO_4 shows

the most significant catalytic activity, but its effect is negligible compared with that of light irradiation and humidity.

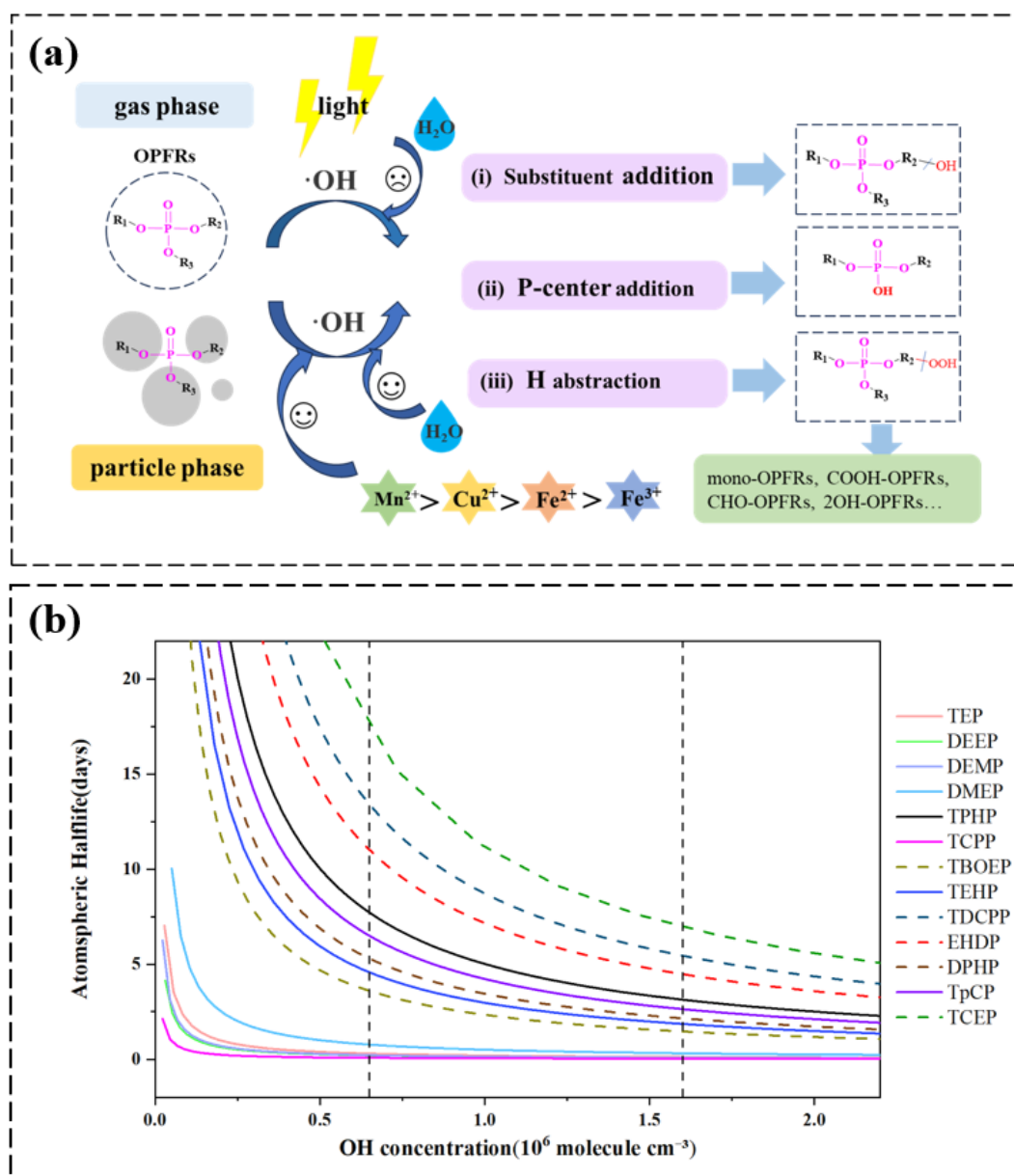


Figure 3. Photodegradation mechanisms and atmospheric half-lives of OPFRs. **(a)** Schematic illustration of OPFR photodegradation in the gas phase and particle phase. **(b)** Estimated atmospheric half-lives of OPFRs. Solid lines represent the gas phase; dashed lines represent the particle phase. Atmospherically relevant range: global mean OH concentration 6.5×10^5 – $1.6 \times 10^6 \text{ molecules cm}^{-3}$. (DEEP: Diethyl ethyl phosphonate; DEMP: Diethyl methyl phosphonate; DMEP: Dimethyl ethyl phosphonate).

Besides hydroxyl radicals, the contribution of other reactive species in the atmosphere to the degradation of OPFRs cannot be overlooked. Huo et al. [54] calculated using DFT that although the oxidizing capacity of $\cdot\text{OH}$ in the atmosphere exceeds that of O_3 , higher concentrations of O_3 serve as the primary oxidant for diphenyl phosphate (DPHP) in the near-surface troposphere. The corresponding atmospheric lifetime of O_3 is only 4 min, significantly shorter than the oxidation lifetime of $\cdot\text{OH}$ (43 days). Wu et al. [55] found that in the cloud water environment of urban

polluted areas and remote regions, the contribution of sulfate radicals ($\text{SO}_4^{\cdot-}$) and organic tri-excited states ($^3\text{C}^*$) to TPHP transformation exceeded that of $\cdot\text{OH}$, accounting for 85.8% and 59.2%, respectively.

Current atmospheric studies mainly focus on single-OPFR oxidation or particle-phase heterogeneous reactions, whereas the influence of coexisting pollutants such as NO_x , VOCs, and complex PM components remains poorly understood. Future studies should evaluate OPFR transformation under multi-pollutant atmospheric conditions.

3.2.2. Photolysis of OPFRs in Aqueous Solutions

There are few reports on the photochemical reactions of OPFRs in aquatic environments under natural light conditions. Cristale et al. [56] investigated the photodegradation of nine OPFRs in river water. The $^1\text{O}_2$ -mediated reaction was the main photolysis pathway of OPFRs, and the photolytic reactivity of alkyl OPFRs and aryl OPFRs was much higher than that of chlorinated OPFRs. Li et al. [57] experimentally determined the $\cdot\text{OH}$ reaction rate constants of 18 OPFRs in aqueous solutions to be 4.0×10^8 – $1.6 \times 10^{10} \text{ M}^{-1}\text{s}^{-1}$, with estimated half-lives in natural water bodies ranging from 0.5 to 22,791.3 days. Most Cl-OPFRs and long-chain alkyl OPFRs exhibit half-lives > 60 days, demonstrating significant persistence.

Dissolved organic matter and inorganic ions in natural water bodies influence the photolysis of OPFRs. NO_2^- and Fe^{3+} accelerate the photolysis rate of TCP by promoting radical generation, whereas humic acid inhibits its photolysis through competition for light energy and quenching effects [58]. Polystyrene microplastics (PS-MPs) in aqueous solutions promote TCEP photolysis by generating $\cdot\text{OH}$, O_2^- and $^1\text{O}_2$. When PS-MPs concentrations range from 0.005 to 5.0 g/L, the TCEP photolysis rate increases by a factor of 1.33–2.35. At concentrations exceeding 5.0 g/L, degradation is inhibited due to light-shielding effects. Moreover, Cl^- , Br^- , HCO_3^- , NO_3^- , NH_4^+ , Mg^{2+} and Ca^{2+} ions present in natural water bodies suppress PS-MPs-mediated TCEP photolysis by consuming $\cdot\text{OH}$ radicals and generating less reactive species [59].

3.3. Biodegradation

3.3.1. Microbial Degradation

Numerous bacterial strains have been reported to possess the ability to degrade OPFRs, including *Klebsiella*, *Pseudomonas*, *Sphingomonas*, and *Bacillus*. *Rhodococcus pyridinivorans* YC-MTN efficiently degrades four aromatic OPFRs, achieving a degradation rate exceeding 80% within 72 h [60]. *Stutzerimonas frequens* RL-XB02 can completely degrade 50 mg/L TPHP within 24 h, with a half-life of only 4.388 h [61]. The major metabolic pathways of OPFRs in organisms are summarized in Figure 4. Hydrolysis of the phosphate ester bond, methylation, and hydroxylation are common pathways for the microbial transformation of OPFRs. The corresponding phosphatase genes, monooxygenase genes, methyltransferase genes, and dehydrogenase genes are the key genes encoding the degradation of OPFRs. Hou et al. [62] studied the aerobic microbial degradation of three non-chlorinated OPFRs: TBOEP, TnBP, and TPHP. Phosphate diesters produced by hydrolysis were the main TPs, with conversion rates of 41.7%, 21.5%, and 47.8%, respectively. Microorganisms can also transform OPFRs via phase II metabolism. Hou et al. [62] first detected the sulfate conjugate product derived from DPHP under aerobic conditions in activated sludge. Yu et al. [63] identified 12 intermediate products during the microbial degradation of TPHP, including glutathione (GSH) and glucose conjugates.

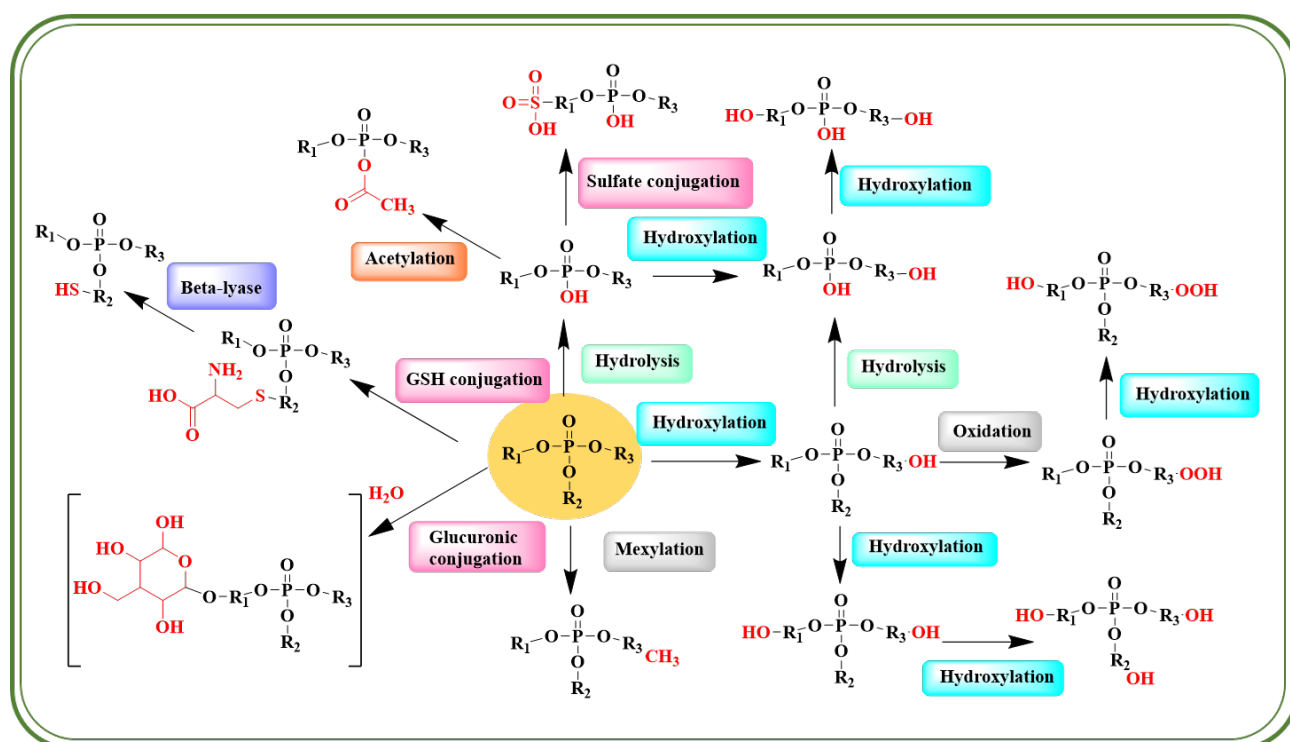


Figure 4. Major metabolic pathways of OPFRs in organisms, including hydroxylation, oxidation, methylation, acetylation, glucuronide conjugation, and sulfate conjugation.

Compared to non-chlorinated OPFRs, chlorinated OPFRs are less readily biodegradable by microorganisms. The degradation rate of TCPP in constructed wetlands over 60 days was only 26% to 28% [64]. Kawagoshi et al. [65] investigated the biodegradation of eight OPFRs in solid waste leachate: under aerobic conditions, no significant biodegradation of TCPP was observed over 80 days, with aryl OPFRs exhibiting the highest degradation rates followed by alkyl OPFRs. Under anaerobic conditions, only the aryl OPFRs TCP and TPHP showed concentration reductions within 60 days. OPFRs exhibit poor degradation efficiency in aerobic composting and anaerobic digestion processes, with total removal rates of 18.9% and 28.9% for the five OPFRs TnBP, TCEP, TPHP, TCPP, TBOEP [66].

Research on the anaerobic degradation of OPFRs is limited, potentially involving distinct degradation pathways in aerobic environments. Under aerobic conditions, microbial hydrolysis of TnBP primarily relies on P-O bond cleavage [67], whereas in anaerobic soils, C-O bond cleavage generates di-n-butyl phosphate (DnBP) [68]. As organophosphorus pollutants, OPFRs can serve as potential phosphorus sources for microbial growth. Adding OPFRs can mitigate the increase in alkaline phosphatase (ALP) activity caused by phosphorus deficiency in microorganisms [69]. In biological nitrogen removal systems, phosphorus limitation can induce enhanced microbial ALP activity, improving TnBP degradation efficiency [70].

Current research on the microbial degradation of OPFRs is largely confined to degradation experiments using single strains or screened enriched microbial communities (Table S5), with limited understanding of the natural degradation processes of OPFRs in surface water and soil environments. It has been reported that the degradation rate of TnBP in anoxic soil reached only 39.8% after 120 days [68]. Castro-Jiménez et al. [71] tested the biodegradation of seven OPFRs in coastal sediments, observing half-lives ranging from 16.8 to 46.8 days, indicating higher persistence compared to sludge tests. Additionally, due to the lack of reference standards for TPs, little is known about the biodegradability of these TPs. The *Sphingomonas* strain TCM1 isolated by Takahashi et al. could degrade TCEP and TDCPP but failed to effectively process the toxic byproducts 2-chloroethanol and 1,3-dichloroisopropanol it produced [72]. In sediment microcosms, TCEP converted to bis (2-chloroethyl) phosphate (BCEP) at a rate of approximately 37.3%, with BCEP concentrations remaining stable over 36 h [73], limiting the ultimate mineralization of TCEP. The YC-MTN strain isolated by Long et al. [60] almost completely degraded TPHP (99.24%) within 72 h, but the mineralization rate after 7 days was only 52.07%, indicating that half of the TPHP still existed as TPs.

In short, OPFRs are difficult to be completely mineralized by microorganisms. Their transformation

processes are closely related to experimental conditions, microbial species, and the structure of OPFRs themselves, with hydrolysis, hydroxylation, and methylation being the dominant reactions. Compared with the enriched or isolated degrading strains reported in the literature, it should be noted that OPFRs may degrade much more slowly and follow more complex transformation pathways in natural environments.

3.3.2. Plant Transformation

Researchers have investigated the plant transformation processes of OPFRs in wheat, rice, white lupine, and ryegrass, primarily through hydroponic experiments. Overall, chlorinated-OPFRs may be more difficult for plants to transform than aryl- and alkyl-substituted OPFRs [74]. Highly hydrophobic OPFRs are more readily absorbed by roots, while less hydrophobic OPFRs are more readily transported from roots to other plant parts. The transformation of OPFRs in plants can be divided into two stages, with transformation pathways varying depending on substituent differences. In Phase I metabolism, chlorinated OPFRs undergo oxidation/reduction dechlorination, hydrolysis, and hydroxylation reactions; non-chlorinated OPFRs primarily undergo hydrolysis and hydroxylation, potentially forming monoester metabolites [75]. The transformation mechanism of alkyl-OPFRs in lettuce is associated with their side chain lengths. TPP, TnBP and triphenyl phosphate (TPeP) with medium chain lengths are more prone to metabolic transformation, while those substituted with longer or shorter alkyl chains may participate in metabolism to a lesser extent via transpiration or lipid adsorption. Hydroxylation serves as the primary metabolic process of alkyl-OPFRs, and the degree of hydroxylation exhibits a decreasing trend with the elongation of alkyl chains [76]. The cell wall and vacuole are the primary sites for their hydrolysis in plants [77]. Acid phosphatase (ACP) is the key enzyme catalyzing the hydrolysis of OPFRs. Particularly under phosphorus-deficient environmental conditions, plants produce and secrete large amounts of ACP, accelerating the hydrolysis of OPFRs both within the plant and in exposed solutions [74].

Phase II reactions are biosynthetic, as active enzymes conjugate Phase I metabolites to endogenous polar molecules, yielding conjugates. Many highly polar endogenous compounds (e.g., sugars, amino acids, sulfates) serve as conjugates, with most resulting conjugates being ionized and highly water-soluble. Additionally, specialized active transport systems recognize the conjugation sites, facilitating transmembrane translocation and enhancing excretion rates [78]. During Phase II metabolism, chlorinated OPFRs form glutathione conjugates, while non-chlorinated OPFRs generate glucuronide conjugates. Aryl OPFRs also yield methoxylated products after hydroxylation [79]. Phosphodiesterases produced through plant biotransformation exhibit higher transport

coefficients than directly exposed parent OPFRs. Palmitoyl-bound metabolites also demonstrate enhanced upward transport capacity due to their greater lipophilicity [80]. These findings further underscore the necessity of considering biotransformation processes as critical factors in the accumulation and translocation of OPFRs within plants.

3.3.3. Animal/Human Metabolism

Experiments have investigated the metabolism of OPFRs *in vivo* and *in vitro* using various animal models, including mice, zebrafish, chicken embryonic stem cells, and human liver microsomes. Previous studies indicate that OPFRs undergo Phase I and Phase II biotransformation into metabolites. The primary functions of Phase I and Phase II metabolism involve increasing product polarity through hydroxylation or conjugation with highly polar groups (e.g., glucuronic acid) to facilitate excretion. Highly hydrophilic OPFRs are eliminated more readily. Differences in substituents during biotransformation significantly influence OPFR conversion efficiency, with alkyl-OPFRs generally being eliminated faster than aryl- and Cl-OPFRs [81]. Wang et al. [82] employed *in vitro* cultures of S9 fractions from crucian carp, catfish, and yellow catfish to observe the metabolism of OPFRs in three different trophic levels. Results indicated that lower-trophic-level fish metabolized EHDP more rapidly. TPHP and TmCP exhibited stable metabolism across all three fish species with no significant differences, while TCEP, TCIPP, and TDCIPP were difficult to metabolize in all fish species. Cao et al. [83] administered 70 µg/kg bw/day TPHP to mice for 7 days and found only 2% of the parent compound was directly excreted via feces and urine, with the majority undergoing metabolic transformation *in vivo*. DPHP was the predominant metabolite detected in all samples (34–58%), indicating hydrolysis as the primary metabolic pathway. Wang et al. [84] studied the bioaccumulation and tissue distribution of TPHP and its metabolites in zebrafish, showing DPHP concentrations up to three times higher than the parent compound in liver and intestinal tissues. Yang et al. [85] identified 10 phase I and 5 phase II metabolites of EHDP in zebrafish, with hydroxylation, glucosylation, and sulfation as the primary metabolic pathways. Hydroxylated metabolites accounted for 47.48% of the total, and metabolism primarily occurred in the liver and intestine.

4. Occurrence of Transformation Products in the Environment

Based on literature compilation, we summarized the number of reported TPs for various parent OPFRs (Table S6). A total of 463 TPs were documented for 25 parent OPFRs included in this survey. Tables S7–S9 provide the detailed structures, SMILES strings and molecular formulas of the collected TPs. Notably, among the 56 OPFRs in

commercial use worldwide, transformation product data remain unavailable for more than 50% of these compounds. In terms of transformation pathways, more products were derived from biotransformation (297) than photodegradation (194), with 28 products shared by both processes. This indicates similar reaction routes can be triggered by photochemical oxidation and microbial metabolism for some OPFRs. More than 50 reported TPs have been identified for TBOEP and TEHP. Compounds bearing long alkyl side-chains or aromatic rings are more prone to sequential degradation, yielding diverse intermediate products.

The major reaction pathway of each TP was identified by comparing the SMILES structures of the parent compound and its corresponding TPs: a total of 562, 300, 214, and 262 transformation pathways were identified for photodegradation, microbial degradation, plant transformation, and animal metabolism, respectively. Among the various reviewed chemical reactions, eleven of them occurred very frequently: hydroxylation, hydrolysis, oxidation, methylation, carboxylation, glucuronide conjugation, dealkylation, sulfate conjugation, glucoside conjugation, GSH conjugation and cysteine formation (Figure 5). Among three biotransformation pathways, hydroxylation (>30%) and hydrolysis (>29%) were the dominant reaction types, a pattern consistent with the biotransformation of pharmaceuticals and personal care products (PPCPs) [86]. However, there were specificities in the distribution of minor reactions. Compared with microbial degradation, methylation accounted for a higher proportion in both animal metabolism and plant transformation; moreover, dealkylation was particularly prominent in plant systems, representing 11.7% of all transformation reactions.

An increasing number of studies have begun to include OPFR TPs in environmental monitoring; however, due to the lack of reference standards, monitoring data remain limited. Figure 6 presents the targeted detection of TPs across various environmental media, including 13 di-OPFRs and 6 OH TPs derived from 14 OPFRs. Full names and abbreviations of these TPs are listed in the caption of Figure 6, and abbreviations are used hereafter for brevity. TPs have been most frequently reported in human body fluids. In urine samples, the detection frequencies of metabolites such as BCEP, BDCIPP, DPHP, and DnBP generally exceed 60% [87,88]. In elderly Chinese individuals, the detection rates of BEHP, BDCIPP, and DPHP were above 75%, with median concentrations of 0.146, 0.121, and 0.089 ng/mL, respectively [87]. Another study reported consistent detection of BCEP, DPHP, and BDCIPP in a multi-regional Chinese population, with concentrations significantly influenced by factors such as age, diet, and living environment [89]. Notably, the detection frequency of BDCIPP in a college student population reached 100%, and the median concentration (7.62 ng/mL) was significantly higher than that in the

general population, suggesting a higher exposure risk in young people or specific living environments [90]. In addition to diester products, hydroxylated metabolites were also frequently detected in urine. BCIPHIPP had a detection frequency of 89.1% and a median concentration of 0.68 ng/mL, while BBOEHP and 5-OH-EHDP showed

detection frequencies of 54.3% and 82.6%, respectively [89]. In urine samples from pregnant Canadian women, the detection frequency of BCIPHIPP was 82.0%, indicating that hydroxylation is a non-negligible transformation pathway of OPFRs in humans [88].



Figure 5. Overview of identified TPs of OPFRs and their transformation pathways. (a) Number of identified TPs for each parent OPFR compound; (b–d) Relative distribution of transformation pathway types for OPFRs under (b) microbial degradation (300 reactions), (c) plant transformation (214 reactions), (d) animal metabolism (262 reactions).

Some TPs also appear frequently in blood matrices. In the blood of non-occupationally exposed adults in Jiangsu Province, BEHP was detected at a frequency of 99% with a median concentration of 1.2 ng/mL, while DPHP and DnBP had detection frequencies of 76% and 60%, respectively [91]. Among occupational workers in e-waste dismantling areas, the median concentration of Σ di-OPFRs in plasma (3.51 ng/mL) was significantly higher than that in serum (0.36 ng/mL) and whole blood (0.23 ng/mL), with BDCIPP and DPHP being the major contributors [92]. Breastfeeding is a major route of infant exposure to OPFR TPs. An analysis of 50 breast milk samples from the United States showed that DnBP had a median concentration as high as 7.44 ng/mL, accounting for 97% of the total di-ester concentration, whereas its parent compound TnBP was present at only 0.439 ng/mL [93]. In the same study, DPHP had a detection frequency of 88% and a median concentration of 0.126 ng/mL. In breast milk from Chinese mothers, the median concentration of BDCIPP

(1.29 pmol/mL) was also higher than that of its parent TDCIPP (0.212 pmol/mL) [94].

OPFR TPs are widely present in various environmental media, including air, water, and soil. In the atmosphere of New York City, the total concentration of ten identified OPFR TPs reached 12,000 pg/m³, comparable to the simultaneously detected parent OPFR concentration (13,000 pg/m³) [46]. In 25 municipal wastewater treatment plants in China, di-OPFRs accounted for 53% of the total OPFRs concentration [95]. Li et al. [96] detected several OH-OPFRs, including BCIPHIPP and 3-OH-TBOEP, in agricultural soils surrounding a plastic recycling industrial park, with a total median concentration of 0.04 ng/g dw. Chen et al. [97] identified five microbial TPs in soil and groundwater around a chemical industrial park, with total concentrations ranging from 3.60 to 270.63 ng/g dw. Notably, TPs have also been repeatedly detected in various foods and drinking water, indicating that dietary intake is an important pathway for human exposure to TPs. In an Australian food survey, the total concentration

of metabolites of nine OPFRs in eggs was 11 times that of the parent OPFRs [98]. In a study by Chen et al. [99], the average total concentrations of six di-OPFRs in milk, powdered milk, and breast milk were 364 ng/L, 2.62 ng/g, and 1850 ng/L, respectively. In an agricultural plastic greenhouse in Tianjin, China, the median total concentrations of 11 di-OPFRs and 5 OH-OPFRs in air, rhizosphere soil, and crops were 526 pg/m³, 42.0 ng/g, and 178 ng/g, respectively [100].

Metabolites of OPFRs have been widely detected in wastewater, food, air, dust, and human samples, with diester concentrations sometimes even exceeding those in the parent compound. Due to a lack of reference standards, only a few metabolites have been included in routine monitoring, and existing studies have limited geographical coverage. There is an urgent need to develop high-throughput screening methods to expand the scope of monitoring.



Figure 6. Detection of OPFR TPs in various environmental media. Abbreviations: DPHP: diphenyl phosphate; OH-TPHP: hydroxylated triphenyl phosphate; DoCP: di-o-cresyl phosphate; DmCP: di-m-cresyl phosphate; DiBP: diisobutyl phosphate; DnBP: di-n-butyl phosphate; DMP: dimethyl phosphate; DPP: dipropyl phosphate; DEP: diethyl phosphate; BCIPP: bis(1-chloro-2-propyl) phosphate; BCEP: bis(2-chloroethyl) phosphate; OH-TCEP: hydroxylated tris(2-chloroethyl) phosphate; BDCIPP: bis(1,3-dichloro-2-propyl) phosphate; BCIPHIPP: bis(1-chloro-2-propyl) 1-hydroxy-2-propyl phosphate; BBOEP: bis(2-butoxyethyl) phosphate; BBOEHEP: bis(2-butoxyethyl) 2-hydroxyethyl phosphate; 3-OH-BBOEP: 3-hydroxy-bis(2-butoxyethyl) phosphate; BEHP: bis(2-ethylhexyl) phosphate; 5-OH-EHP: 5-hydroxy-2-ethylhexyl diphenyl phosphate. The molecular structures of the above TPs are provided in Tables S7–S9 of the Supplementary Information.

5. Toxicological Effects of Transformation Products

Most studies have shown that TPs of OPFRs adversely affect the endocrine system, development, and reproduction in mice, fish, and humans.

Both *in vivo* and *in vitro* toxicological studies have confirmed that TPs possess cytotoxic, endocrine-disrupting, and neurotoxic properties. Su et al. [101] found that DPHP, the hydrolysis product of TPHP, altered significantly more genes in chicken embryonic hepatocytes than the parent compound TPHP. Using fluorescence quenching experiments, Wang et al. [102]

demonstrated that DnBP and DEP bind to the protein GB1, inducing secondary structural changes through non-covalent interactions and thereby interfering with protein function. BDCIPP induces oxidative stress and DNA damage, impairs triglyceride hydrolysis, and accelerates aging in *Caenorhabditis elegans* [103]. After 12 weeks of low-dose DPHP exposure in mice, hepatic glycogen content decreased by 9.8%, serum glucose levels dropped by 38.5%, and insulin resistance developed. Meanwhile, DPHP accumulated in brain tissue and reduced the levels of five neurotransmitters, including L-glutamate and

serotonin, by 15.4–60.8% [31]. Another study also showed that low-dose DPHP significantly disturbed hepatic fatty acid β -oxidation and acylcarnitine metabolism, suppressed body weight gain, and exhibited clear hepatotoxicity [104]. In zebrafish, DPHP induced cardiac developmental defects, mitochondrial dysfunction, hepatotoxicity, and nephrotoxicity [105]; exposure to BCIPP, BDCIPP, and DPHP all resulted in increased mortality, reduced hatching rates, and multiple malformations, with the toxicity order being BCIPP $\geq$ BDCIPP > DPHP [106]. Furthermore, Noyes et al. [107] demonstrated that the teratogenic effect of BDCIPP in zebrafish is four orders of magnitude higher than that of its parent compound TDCIPP.

Multiple studies have reported hormonal disruption by OPFR TPs. Kojima et al. [108] examined the nuclear receptor activities of 12 OPFR metabolites and found that the hydroxylated TPHP metabolites 4-hydroxyphenyl diphenyl phosphate (HO-p-TPHP) and 3-hydroxyphenyl diphenyl phosphate (HO-m-TPHP) exhibited much stronger estrogen receptor (ER α and ER β) agonistic activities than the parent compound. Specifically, the ER α agonistic activity of HO-p-TPHP was more than 10-fold higher, and its ER β activity 20-fold higher, than those of TPHP. In addition, BBOEHP and BDCIPP have also been reported to possess potential ER α agonistic activity [106]. Yeast two-hybrid assays showed that the TpCP metabolites 4-hydroxyphenyl di-p-tolyl phosphate (4-OH-DpCP) and 3-hydroxy-4-methylphenyl di-p-tolyl phosphate (3-OH-DpCP) exhibited anti-androgenic activities 5.8- and 5.3-fold higher than the parent compound [109]. Using molecular docking and DFT calculations, Tariq et al. [110] demonstrated that BCIPP, BDCIPP, and DPHP have strong binding affinities for the human mineralocorticoid receptor, potentially disrupting normal protein function. DnBP and 3-hydroxybutyl di-n-butyl phosphate (3-OH-TnBP) significantly inhibit ER α activity, leading to a gestational diabetes-like phenotype in pregnant mice, including hyperglycemia, insulin resistance, and glucose intolerance, and the metabolite 3-OH-TnBP exhibits stronger toxic effects than the parent compound [111].

Epidemiological studies further confirm associations between OPFR metabolite exposure and human organ function, diseases, and fetal development. Among U.S. adolescents aged 12–19 years, elevated urinary BCEP levels were significantly associated with lower fasting insulin and impaired insulin homeostasis, suggesting that BCEP may increase the risk of insulin resistance and diabetes [112]. Using data from the 2011–2012 National Health and Nutrition Examination Survey (NHANES), Hu et al. [113] found that urinary concentrations of DPHP, BDCIPP, and BCEP were significantly correlated with a modest decline in lung function, with more pronounced effects for mixed exposure. Nan et al. [114] also used NHANES data (2011–2018) to show positive associations between DnBP and BCEP exposure and the prevalence of

sarcopenia. In pregnant women, urinary levels of BBOEP and 4-hydroxyphenyl phenyl phosphate (4-OH-DPHP) were negatively correlated with newborn birth weight, indicating that fetuses are susceptible to the developmental toxicity of BDCIPP and BBOEP during gestation [115]. Further research is needed to investigate the molecular mechanisms and health risks underlying the adverse effects induced by OPFR TPs.

Due to limited standards, some researchers have used quantitative structure–activity relationship (QSAR)-based predictive models to estimate the toxicity of TPs. Choi et al. [116] detected 6, 9, and 18 TPHP TPs in green algae, *Daphnia*, and medaka, respectively, via non-target screening, and four of these were predicted to be more toxic than the parent compound. Wu et al. [59] predicted 14 interaction products between TCEP and microplastics, three of which were chlorinated aromatic products with significantly higher toxicity than TCEP. Liu et al. [46] found that a substantial fraction (24–89%) of the investigated TPs were predicted to be more toxic than their parents, and that atmospheric transformation of most OPFRs would increase the overall risk to aquatic and terrestrial organisms. Lao et al. [117] assessed the ecological risk of 11 organophosphate esters and 6 TPs in wastewater discharge in Hong Kong and reported an approximately 38% increase in total risk when TPs were taken into account.

In summary, current toxicological studies have primarily focused on a limited number of di-OPFRs and a few hydroxylated products. Moreover, OPFRs often co-exist with multiple TPs in the environment, necessitating reliable methods to elucidate the synergistic or antagonistic effects of combined exposure. From an environmental perspective, toxicology studies are often performed with exposure concentrations several magnitudes higher than those in real aquatic environments. The chronic toxicities at or close to environmental concentrations remain largely unrevealed and should be scrutinized.

6. Conclusions and Perspectives

This study broadens the knowledge on the environmental fate and toxic effects of OPFRs from the perspective of transformation and the generated TPs. New findings emerged from the data analysis which also allowed to highlight several data gaps and research needs:

(1) Abiotic hydrolysis contributes negligibly to the attenuation of OPFRs in natural environments, and OPFR degradation primarily relies on photolysis and biotransformation. Photolysis is influenced by multiple factors including humidity, particle size, and inorganic ions, while biotransformation kinetics exhibit significant heterogeneity. Cl-OPFRs consistently demonstrate higher environmental persistence across all media compared with alkyl and aryl analogs. However, current understanding is

largely biased toward idealized high-concentration laboratory conditions and single-strain microbial cultures, neglecting transformation in complex atmospheric matrices and more nature-like simulated ecosystems. Future studies should prioritize environmentally relevant concentration experiments in multi-medium coupled systems to improve the predictability of OPFR environmental fate under realistic conditions.

(2) This review summarizes a total of 463 TPs from 25 OPFRs; however, the data distribution is significantly skewed: a few well-studied compounds such as TPHP, EHDP, TDCIPP, and TBOEP account for the vast majority of TPs, while transformation data for emerging aryl and Cl-OPFRs with complex structures, such as V6, RDP, and CDP, remain virtually absent. Future studies should strengthen research on the transformation behavior of these emerging, structurally complex OPFRs. Twenty-eight TPs of OPFRs are notable for being formed under both biotic and abiotic conditions. These TPs would therefore be ubiquitous since they were produced under various conditions and in several matrices and should be placed on priority lists for environmental monitoring.

(3) Biological hydrolysis and hydroxylation are the common dominant transformation pathways of OPFRs across microorganisms, plants, and animals; however, secondary pathways including dealkylation, carboxylation, and phase II conjugation reactions exhibit significant interspecies heterogeneity. Future studies should systematically investigate the transformation, distribution, and bioaccumulation mechanisms of TPs across organisms at different trophic levels and among species, in order to reveal species-specific metabolic patterns and their transfer and biomagnification in food chains, thereby providing mechanistic support for the ecological risk assessment of OPFRs.

(4) Owing to the lack of authentic reference standards, most TPs have not yet been incorporated into routine environmental monitoring. Among the reported TPs, DPHP, DnBP, BDCIPP, and BEHP are frequently detected and exhibit greater endocrine-disrupting potency than their parent compounds, thereby warranting particular attention in future monitoring and risk assessment. From a toxicological viewpoint, the lack of mechanistic information needed for predictive toxicology and risk assessment of these chemicals is also striking. More studies investigating the modes of action of these compounds are urgently needed. Additionally, the limited availability of reference standards for several TPs makes it difficult to test their toxicity to living organisms.

Supplementary Materials

The additional data and information can be downloaded at: <https://media.sciltp.com/articles/others/2609281026482980/GES-26030040-SI.zip>. Table S1: PRISMA 2020 Checklist. Table S2: Complete reference list of articles included in our analysis. Table S3: Hydrolysis

rates of OPFRs in near-neutral solutions. Table S4: Reaction kinetics of OPFRs with $\cdot\text{OH}$ in the atmosphere. Table S5: Microbial degradation efficiency of OPFRs. Table S6: The number of reported transformation products of OPFRs. Table S7: List of Alkyl-OPFRs transformation products. Table S8: List of Cl-OPFRs transformation products. Table S9: List of Aryl-OPFRs transformation products. References [118–191] are cited in the Supplementary Materials.

Author Contributions

L.J.: Investigation, writing—original draft preparation. Y.S.: Investigation, writing—review & editing. Y.Z.: Resources, data curation. Y.H.: Resources. S.X.: Writing—review & editing. Q.B.: Conceptualization, funding acquisition, supervision. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the National Key Research and Development Program of China (2024YFC3908601), and National Natural Science Foundation of China (42277406).

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Not applicable.

Acknowledgments

We are grateful to the Editor, the Editorial Assistant and anonymous reviewers for improving the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used DeepSeek to correct grammar, optimize language phrasing, and assist with formatting checks. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

References

- Keimowitz, A.R.; Strunsky, N.; Wovkulich, K. Organophosphate flame retardants in household dust before and after introduction of new furniture. *Chemosphere* **2016**, *148*, 467–472. <https://doi.org/10.1016/j.chemosphere.2016.01.048>.
- van der Veen, I.; de Boer, J. Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity

- and analysis. *Chemosphere* **2012**, *88*, 1119–1153. <https://doi.org/10.1016/j.chemosphere.2012.03.067>.
3. Ma, H.; Wang, C.; Suo, H.; et al. Global gridded emission inventory of organophosphate flame retardants from 2010 to 2020. *Environ. Sci. Technol.* **2024**, *58*, 17070–17080. <https://doi.org/10.1021/acs.est.4c06504>.
 4. Huang, J.; Ye, L.; Fang, M.; et al. Industrial production of organophosphate flame retardants (OPFRs): Big knowledge gaps need to be filled? *Bull. Environ. Contam. Toxicol.* **2022**, *108*, 809–818. <https://doi.org/10.1007/s00128-021-03454-7>.
 5. Greaves, A.K.; Letcher, R.J. A review of organophosphate esters in the environment from biological effects to distribution and fate. *Bull. Environ. Contam. Toxicol.* **2017**, *98*, 2–7. <https://doi.org/10.1007/s00128-016-1898-0>.
 6. Alghamdi, M.; Abdallah, M.A.-E.; Harrad, S. The utility of X-Ray fluorescence spectrometry as a tool for monitoring compliance with limits on concentrations of halogenated flame retardants in waste polymers: A critical review. *Emerg. Contam.* **2022**, *8*, 9–20. <https://doi.org/10.1016/j.emcon.2021.12.002>.
 7. Yao, C.; Yang, H.; Li, Y. A review on organophosphate flame retardants in the environment: Occurrence, accumulation, metabolism and toxicity. *Sci. Total Environ.* **2021**, *795*, 148837. <https://doi.org/10.1016/j.scitotenv.2021.148837>.
 8. Wang, Z.; Qi, A.; Lv, J.; et al. Occurrence and seasonal variations of organophosphate flame retardants in air and dust from college microenvironments at Qingdao, China: Implications for student's exposure and risk assessment. *Sci. Total Environ.* **2024**, *937*, 173182. <https://doi.org/10.1016/j.scitotenv.2024.173182>.
 9. Chen, M.; Jiang, J.; Gan, Z.; et al. Grain size distribution and exposure evaluation of organophosphorus and brominated flame retardants in indoor and outdoor dust and PM10 from Chengdu, China. *J. Hazard. Mater.* **2019**, *365*, 280–288. <https://doi.org/10.1016/j.jhazmat.2018.10.082>.
 10. Kim, U.J.; Kannan, K. Occurrence and distribution of organophosphate flame retardants/plasticizers in surface waters, tap water, and rainwater: Implications for human exposure. *Environ. Sci. Technol.* **2018**, *52*, 5625–5633. <https://doi.org/10.1021/acs.est.8b00727>.
 11. Han, F.; Chen, G.; Tao, G.; et al. Thyroid-disrupting effects caused by exposure to alternative flame retardants from groundwater contamination in rural central China. *Sci. Total Environ.* **2022**, *839*, 156300. <https://doi.org/10.1016/j.scitotenv.2022.156300>.
 12. Casas, G.; Martinez-Varela, A.; Vila-Costa, M.; et al. Rain amplification of persistent organic pollutants. *Environ. Sci. Technol.* **2021**, *55*, 12961–12972. <https://doi.org/10.1021/acs.est.1c03295>.
 13. Hu, Y.X.; Sun, Y.X.; Li, X.; et al. Organophosphorus flame retardants in mangrove sediments from the pearl river estuary, south China. *Chemosphere* **2017**, *181*, 433–439. <https://doi.org/10.1016/j.chemosphere.2017.04.117>.
 14. Wang, Y.; Sun, H.; Zhu, H.; et al. Occurrence and distribution of organophosphate flame retardants (OPFRs) in soil and outdoor settled dust from a multi-waste recycling area in China. *Sci. Total Environ.* **2018**, *625*, 1056–1064. <https://doi.org/10.1016/j.scitotenv.2018.01.013>.
 15. Zhang, X.; Zou, W.; Mu, L.; et al. Rice ingestion is a major pathway for human exposure to organophosphate flame retardants (OPFRs) in China. *J. Hazard. Mater.* **2016**, *318*, 686–693. <https://doi.org/10.1016/j.jhazmat.2016.07.055>.
 16. Bekele, T.G.; Zhao, H.; Wang, Q.; et al. Bioaccumulation and trophic transfer of emerging organophosphate flame retardants in the marine food webs of Laizhou Bay, North China. *Environ. Sci. Technol.* **2019**, *53*, 13417–13426. <https://doi.org/10.1021/acs.est.9b03687>.
 17. Guo, Y.; Chen, M.; Liao, M.; et al. Organophosphorus flame retardants and their metabolites in paired human blood and urine. *Ecotoxicol. Environ. Saf.* **2023**, *268*, 115696. <https://doi.org/10.1016/j.ecoenv.2023.115696>.
 18. Qiao, L.; Zheng, X.B.; Zheng, J.; et al. Legacy and currently used organic contaminants in human hair and hand wipes of female e-waste dismantling workers and workplace dust in South China. *Environ. Sci. Technol.* **2019**, *53*, 2820–2829. <https://doi.org/10.1021/acs.est.8b05503>.
 19. Chen, Y.; Cao, Z.; Covaci, A.; et al. Novel and legacy flame retardants in paired human fingernails and indoor dust samples. *Environ. Int.* **2019**, *133*, 105227. <https://doi.org/10.1016/j.envint.2019.105227>.
 20. Brommer, S.; Jantunen, L.M.; Bidleman, T.F.; et al. Determination of vapor pressures for organophosphate esters. *J. Chem. Eng. Data* **2014**, *59*, 1441–1447. <https://doi.org/10.1021/je401026a>.
 21. Hong, X.; Yuan, L.; Zhao, X.; et al. Embryonic exposure to organophosphate flame retardants (OPFRs) differentially induces cardiotoxicity in rare minnow (*Gobiocypris rarus*). *Environ. Sci. Technol.* **2024**, *58*, 13648–13657. <https://doi.org/10.1021/acs.est.4c01927>.
 22. Sun, L.; Xu, W.; Peng, T.; et al. Developmental exposure of zebrafish larvae to organophosphate flame retardants causes neurotoxicity. *Neurotoxicol. Teratol.* **2016**, *55*, 16–22. <https://doi.org/10.1016/j.ntt.2016.03.003>.
 23. Hao, Z.; Zhang, Z.; Lu, D.; et al. Organophosphorus flame retardants impair intracellular lipid metabolic function in human hepatocellular cells. *Chem. Res. Toxicol.* **2019**, *32*, 1250–1258. <https://doi.org/10.1021/acs.chemrestox.9b00058>.
 24. Wang, J.; Cui, Y.; Wang, Y.; et al. Tributyl phosphate induced male reproductive toxicity in mice. *Environ. Sci. Technol.* **2025**, *59*, 3000–3012. <https://doi.org/10.1021/acs.est.4c10280>.
 25. Song, Y.; Xu, T.; Zhang, H.; et al. Opposing visual impairments induced by structurally similar organophosphate flame retardants TPHP and CDP in zebrafish larvae. *Environ. Sci. Technol.* **2025**, *59*, 8428–8438. <https://doi.org/10.1021/acs.est.5c00663>.
 26. Hong, Z.; Li, Y.; Deng, X.; et al. Comprehensive analysis of triphenyl phosphate: An environmental explanation of colorectal cancer progression. *Ecotoxicol. Environ. Saf.* **2022**, *241*, 113778. <https://doi.org/10.1016/j.ecoenv.2022.113778>.

- 2022.113778. Correction in *Ecotoxicol. Environ. Saf.* **2022**, *242*, 113911.
27. Zhang, X.; Lu, Z.; Ren, X.; et al. Genetic comprehension of organophosphate flame retardants, an emerging threat to prostate cancer. *Ecotoxicol. Environ. Saf.* **2021**, *223*, 112589. <https://doi.org/10.1016/j.ecoenv.2021.112589>.
 28. Blum, A.; Behl, M.; Birnbaum, L.S.; et al. Organophosphate ester flame retardants: Are they a regrettable substitution for polybrominated diphenyl ethers? *Environ. Sci. Technol. Lett.* **2019**, *6*, 638–649. <https://doi.org/10.1021/acs.estlett.9b00582>.
 29. Zhang, L.; Luo, X.; Fu, J.; et al. Emerging aryl-organophosphate esters in coastal sediments: Comprehensive screening and transformation insights from the Beibu Gulf, China. *Environ. Sci. Technol.* **2025**, *59*, 18294–18305. <https://doi.org/10.1021/acs.est.5c05790>.
 30. Tran-Lam, T.T.; Pham, P.T.; Bui, M.Q.; et al. Organophosphate esters and their metabolites in marine fish from Vietnam: Analytical method development and validation. *J. Food Compos. Anal.* **2024**, *131*, 106266. <https://doi.org/10.1016/j.jfca.2024.106266>.
 31. Cao, J.; Wang, X.; Lei, Y.; et al. Health risks of low-dose dietary exposure to triphenyl phosphate and diphenyl phosphate in mice: Insights from the gut-liver axis. *Environ. Sci. Technol.* **2025**, *59*, 8960–8971. <https://doi.org/10.1021/acs.est.4c08270>.
 32. Tian, Y.X.; Chen, H.Y.; Ma, J.; et al. A critical review on sources and environmental behavior of organophosphorus flame retardants in the soil: Current knowledge and future perspectives. *J. Hazard. Mater.* **2023**, *452*, 131161. <https://doi.org/10.1016/j.jhazmat.2023.131161>.
 33. Zhang, Q.; Wang, Y.; Zhang, C.; et al. A review of organophosphate esters in soil: Implications for the potential source, transfer, and transformation mechanism. *Environ. Res.* **2022**, *204*, 112122. <https://doi.org/10.1016/j.envres.2021.112122>.
 34. Zhou, X.; Wang, C.; Huang, M.; et al. A review of the present methods used to remediate soil and water contaminated with organophosphate esters and developmental directions. *J. Hazard. Mater.* **2024**, *475*, 134834. <https://doi.org/10.1016/j.jhazmat.2024.134834>.
 35. Yang, L.; Yin, Z.; Tian, Y.; et al. A new and systematic review on the efficiency and mechanism of different techniques for OPFRs removal from aqueous environments. *J. Hazard. Mater.* **2022**, *431*, 128517. <https://doi.org/10.1016/j.jhazmat.2022.128517>.
 36. Blumenthal, E.; Herbert, J.B.M. The mechanism of the hydrolysis of trimethyl orthophosphate. *Trans. Faraday Soc.* **1945**, *41*, 611–617. <https://doi.org/10.1039/tf9454100611>.
 37. Tarrat, N. Alkaline hydrolysis of phosphate triesters in solution: Stepwise or concerted? A theoretical study. *J. Mol. Struct. THEOCHEM.* **2010**, *941*, 56–60. <https://doi.org/10.1016/j.theochem.2009.11.001>.
 38. Su, G.; Letcher, R.J.; Yu, H. Organophosphate flame retardants and plasticizers in aqueous solution: pH-dependent hydrolysis, kinetics, and pathways. *Environ. Sci. Technol.* **2016**, *50*, 8103–8111. <https://doi.org/10.1021/acs.est.6b02187>.
 39. Howard, P.H.; Deo, P.G. Degradation of aryl phosphates in aquatic environments. *Bull. Environ. Contam. Toxicol.* **1979**, *22*, 337–344. <https://doi.org/10.1007/bf02026952>.
 40. David, M.D.; Seiber, J.N. Accelerated hydrolysis of industrial organophosphates in water and soil using sodium perborate. *Environ. Pollut.* **1999**, *105*, 121–128. [https://doi.org/10.1016/s0269-7491\(98\)00173-0](https://doi.org/10.1016/s0269-7491(98)00173-0).
 41. Fang, Y.; Kim, E.; Strathmann, T.J. Mineral - and base-catalyzed hydrolysis of organophosphate flame retardants: Potential major fate-controlling sink in soil and aquatic environments. *Environ. Sci. Technol.* **2018**, *52*, 1997–2006. <https://doi.org/10.1021/acs.est.7b05911>.
 42. Li, Y.; Liu, K.; Guo, Y.; et al. Mechanistic insights into facet-dependent catalytic hydrolysis of organophosphate ester by α -MnO₂ nanorods. *Sep. Purif. Technol.* **2025**, *360*, 130940. <https://doi.org/10.1016/j.seppur.2024.130940>.
 43. Saint-Hilaire, D.; Jans, U. Reactions of three halogenated organophosphorus flame retardants with reduced sulfur species. *Chemosphere* **2013**, *93*, 2033–2039. <https://doi.org/10.1016/j.chemosphere.2013.07.028>.
 44. Saint-Hilaire, D.; Ismail, K.Z.; Jans, U. Reaction of tris(2-chloroethyl) phosphate with reduced sulfur species. *Chemosphere* **2011**, *83*, 941–947. <https://doi.org/10.1016/j.chemosphere.2011.02.040>.
 45. Gong, X.; Zhang, W.; Zhang, S.; et al. Organophosphite antioxidants in mulch films are important sources of organophosphate pollutants in farmlands. *Environ. Sci. Technol.* **2021**, *55*, 7398–7406. <https://doi.org/10.1021/acs.est.0c08741>.
 46. Liu, Q.; Li, L.; Zhang, X.; et al. Uncovering global-scale risks from commercial chemicals in air. *Nature* **2021**, *600*, 456–461. <https://doi.org/10.1038/s41586-021-04134-6>.
 47. Yu, Q.; Xie, H.B.; Chen, J. Atmospheric chemical reactions of alternatives of polybrominated diphenyl ethers initiated by $\cdot$ OH: A case study on triphenyl phosphate. *Sci. Total Environ.* **2016**, *571*, 1105–1114. <https://doi.org/10.1016/j.scitotenv.2016.07.105>.
 48. Li, C.; Chen, J.; Xie, H.B.; et al. Effects of atmospheric water on $\cdot$ OH-initiated oxidation of organophosphate flame retardants: A DFT investigation on TCPP. *Environ. Sci. Technol.* **2017**, *51*, 5043–5051. <https://doi.org/10.1021/acs.est.7b00347>.
 49. Li, C.; Zheng, S.; Chen, J.; et al. Kinetics and mechanism of OH-initiated atmospheric oxidation of organophosphorus plasticizers: A computational study on tri-p-cresyl phosphate. *Chemosphere* **2018**, *201*, 557–563. <https://doi.org/10.1016/j.chemosphere.2018.03.034>.
 50. Liu, Y.; Huang, L.; Li, S.M.; et al. OH-initiated heterogeneous oxidation of tris-2-butoxyethyl phosphate: Implications for its fate in the atmosphere. *Atmos. Chem. Phys.* **2014**, *14*, 12195–12207. <https://doi.org/10.5194/acp-14-12195-2014>.
 51. Lao, J.Y.; Lin, H.; Qin, X.; et al. Insights into the atmospheric persistence, transformation, and health implications of organophosphate esters in urban ambient air. *Environ. Sci.*

- Technol.* **2022**, *56*, 12003–12013. <https://doi.org/10.1021/acs.est.2c01161>.
52. Liu, Q.; Liggio, J.; Li, K.; et al. Understanding the impact of relative humidity and coexisting soluble iron on the OH-initiated heterogeneous oxidation of organophosphate flame retardants. *Environ. Sci. Technol.* **2019**, *53*, 6794–6803. <https://doi.org/10.1021/acs.est.9b01758>.
 53. Fan, W.; Zhu, Z.; Zhang, H.; et al. Degradation, transformation and cytotoxicity of triphenyl phosphate on surface of different transition metal salts in atmospheric environment. *Sci. Total Environ.* **2024**, *937*, 173462. <https://doi.org/10.1016/j.scitotenv.2024.173462>.
 54. Huo, Y.; Li, M.; Jiang, J.; et al. The homogeneous and heterogeneous oxidation of organophosphate esters (OPEs) in the atmosphere: Take diphenyl phosphate (DHP) as an example. *Environ. Pollut.* **2023**, *324*, 121395. <https://doi.org/10.1016/j.envpol.2023.121395>.
 55. Wu, Y.; Wu, F.; Brigante, M.; et al. Reactive species-mediated phototransformation of triphenyl phosphate in cloud water: Kinetics, pathways and implications. *Environ. Pollut.* **2025**, *383*, 126717. <https://doi.org/10.1016/j.envpol.2025.126717>.
 56. Cristale, J.; Dantas, R.F.; De Luca, A.; et al. Role of oxygen and DOM in sunlight induced photodegradation of organophosphorous flame retardants in river water. *J. Hazard. Mater.* **2017**, *323*, 242–249. <https://doi.org/10.1016/j.jhazmat.2016.05.019>.
 57. Li, C.; Wei, G.; Chen, J.; et al. Aqueous OH radical reaction rate constants for organophosphorus flame retardants and plasticizers: Experimental and modeling studies. *Environ. Sci. Technol.* **2018**, *52*, 2790–2799. <https://doi.org/10.1021/acs.est.7b05429>.
 58. Sun, S.; Jiang, J.; Zhao, H.; et al. Photochemical reaction of tricresyl phosphate (TCP) in aqueous solution: Influencing factors and photolysis products. *Chemosphere* **2020**, *241*, 124971. <https://doi.org/10.1016/j.chemosphere.2019.124971>.
 59. Wu, N.; Yu, H.; Liu, Z.; et al. The underestimated environmental risk of tris(2-chloroethyl) phosphate photodegradation in aqueous environment induced by polystyrene microplastics. *Water Res.* **2025**, *273*, 123048. <https://doi.org/10.1016/j.watres.2024.123048>.
 60. Long, Y.; Wang, J.; Nwe, M.T.; et al. Biodegradation of aryl-organophosphate flame retardants by *Rhodococcus pyridinivorans* YC-MTN: Performance, pathway and potential in environmental remediation. *Int. Biodeterior. Biodegrad.* **2024**, *190*, 105772. <https://doi.org/10.1016/j.ibiod.2024.105772>.
 61. Ren, L.; Luo, X.; Zhou, J.L.; et al. Biodegradation of triphenyl phosphate by a novel marine bacterial strain: Performance, mechanism, bioremediation and toxicity alleviation. *J. Hazard. Mater.* **2025**, *494*, 138664. <https://doi.org/10.1016/j.jhazmat.2025.138664>.
 62. Hou, R.; Wang, Y.; Zhou, S.; et al. Aerobic degradation of nonhalogenated organophosphate flame esters (OPEs) by enriched cultures from sludge: Kinetics, pathways, bacterial community evolution, and toxicity evaluation. *Sci. Total Environ.* **2021**, *760*, 143385. <https://doi.org/10.1016/j.scitotenv.2020.143385>.
 63. Yu, Y.; Huang, W.; Yu, W.; et al. Metagenomic insights into the mechanisms of triphenyl phosphate degradation by bioaugmentation with *Sphingopyxis* sp. GY. *Ecotoxicol. Environ. Saf.* **2023**, *263*, 115261. <https://doi.org/10.1016/j.jecoenv.2023.115261>.
 64. Qin, P.; Lu, S.; Liu, X.; et al. Removal of tri-(2-chloroisopropyl) phosphate (TCPP) by three types of constructed wetlands. *Sci. Total Environ.* **2020**, *749*, 141668. <https://doi.org/10.1016/j.scitotenv.2020.141668>.
 65. Kawagoshi, Y.; Nakamura, S.; Fukunaga, I. Degradation of organophosphoric esters in leachate from a sea-based solid waste disposal site. *Chemosphere* **2002**, *48*, 219–225. [https://doi.org/10.1016/s0045-6535\(02\)00051-6](https://doi.org/10.1016/s0045-6535(02)00051-6).
 66. Pang, L.; Ge, L.; Yang, P.; et al. Degradation of organophosphate esters in sewage sludge: Effects of aerobic/anaerobic treatments and bacterial community compositions. *Bioresour. Technol.* **2018**, *255*, 16–21. <https://doi.org/10.1016/j.biortech.2018.01.104>.
 67. Liu, J.; Lin, H.; Dong, Y.; et al. Elucidating the biodegradation mechanism of tributyl phosphate (TBP) by *Sphingomonas* sp. isolated from TBP-contaminated mine tailings. *Environ. Pollut.* **2019**, *250*, 284–291. <https://doi.org/10.1016/j.envpol.2019.03.127>.
 68. Wang, G.; Li, M.; Ji, Y.; et al. Insight into natural attenuation of tributyl phosphate by indigenous anaerobic microbes in soils: Implication by stable carbon isotope fractionation and microbial community structures. *Environ. Pollut.* **2025**, *366*, 125482. <https://doi.org/10.1016/j.envpol.2024.125482>.
 69. Vila-Costa, M.; Sebastián, M.; Pizarro, M.; et al. Microbial consumption of organophosphate esters in seawater under phosphorus limited conditions. *Sci. Rep.* **2019**, *9*, 233. <https://doi.org/10.1038/s41598-018-36635-2>.
 70. Lin, Z.; Yan, Z.; Kong, W.; et al. Unveiling the simultaneous organophosphate esters degradation mechanisms in biological wastewater nitrogen removal systems under varying phosphorus source conditions: Microbial insights and ecological interactions. *J. Hazard. Mater.* **2026**, *501*, 140835. <https://doi.org/10.1016/j.jhazmat.2025.140835>.
 71. Castro-Jiménez, J.; Cuny, P.; Milton, C.; et al. Effective degradation of organophosphate ester flame retardants and plasticizers in coastal sediments under high urban pressure. *Sci. Rep.* **2022**, *12*, 20228. <https://doi.org/10.1038/s41598-022-24685-6>.
 72. Takahashi, S.; Satake, I.; Konuma, I.; et al. Isolation and identification of persistent chlorinated organophosphorus flame retardant-degrading bacteria. *Appl. Environ. Microbiol.* **2010**, *76*, 5292–5296. <https://doi.org/10.1128/aem.00506-10>.
 73. Zhou, X.; Liang, Y.; Ren, G.; et al. Biotransformation of tris(2-chloroethyl) phosphate (TCEP) in sediment microcosms and the adaptation of microbial communities to TCEP. *Environ. Sci. Technol.* **2020**, *54*, 5489–5497. <https://doi.org/10.1021/acs.est.9b07042>.

74. Liu, Q.; Wang, X.; Zhou, J.; et al. Phosphorus deficiency promoted hydrolysis of organophosphate esters in plants: Mechanisms and transformation pathways. *Environ. Sci. Technol.* **2021**, *55*, 9895–9904. <https://doi.org/10.1021/acs.est.1c02396>.
75. Wan, W.; Huang, H.; Lv, J.; et al. Uptake, translocation, and biotransformation of organophosphorus esters in wheat (*Triticum aestivum* L.). *Environ. Sci. Technol.* **2017**, *51*, 13649–13658. <https://doi.org/10.1021/acs.est.7b01758>.
76. Wang, Y.; Li, X.; Chen, S.; et al. Structure-dependent distribution, metabolism, and toxicity effects of alkyl organophosphate esters in lettuce (*Lactuca sativa* L.). *Environ. Sci. Technol.* **2024**, *58*, 17441–17453. <https://doi.org/10.1021/acs.est.4c05523>.
77. Gong, X.; Wang, Y.; Pu, J.; et al. The environment behavior of organophosphate esters (OPEs) and di-esters in wheat (*Triticum aestivum* L.): Uptake mechanism, *in vivo* hydrolysis and subcellular distribution. *Environ. Int.* **2020**, *135*, 105405. <https://doi.org/10.1016/j.envint.2019.105405>.
78. Dekant, W. The role of biotransformation and bioactivation in toxicity. In *Molecular, Clinical and Environmental Toxicology*; Birkhäuser Basel: Basel, Switzerland, 2009; Volume 99, pp. 57–86. https://doi.org/10.1007/978-3-7643-8336-7_3.
79. Zhang, Q.; Yao, Y.; Wang, Y.; et al. Plant accumulation and transformation of brominated and organophosphate flame retardants: A review. *Environ. Pollut.* **2021**, *288*, 117742. <https://doi.org/10.1016/j.envpol.2021.117742>.
80. Li, X.; Yao, Y.; Chen, H.; et al. Identification of novel organophosphate esters in hydroponic lettuces (*Lactuca sativa* L.): Biotransformation and acropetal translocation. *Environ. Sci. Technol.* **2022**, *56*, 10699–10709. <https://doi.org/10.1021/acs.est.2c01610>.
81. Fu, Z.; Chen, J.; Wang, Y.; et al. Quantum chemical simulations revealed the toxicokinetic mechanisms of organic phosphorus flame retardants catalyzed by P450 enzymes. *J. Environ. Sci. Health Part C*. **2018**, *36*, 272–291. <https://doi.org/10.1080/10590501.2018.1537564>.
82. Wang, X.; Zhong, W.; Xiao, B.; et al. Bioavailability and biomagnification of organophosphate esters in the food web of Taihu Lake, China: Impacts of chemical properties and metabolism. *Environ. Int.* **2019**, *125*, 25–32. <https://doi.org/10.1016/j.envint.2019.01.018>.
83. Cao, J.; Lei, Y.; Jiang, X.; et al. Biotransformation, bioaccumulation, and bioelimination of triphenyl phosphate and its dominant metabolite diphenyl phosphate *in vivo*. *Environ. Sci. Technol.* **2024**, *58*, 15486–15496. <https://doi.org/10.1021/acs.est.4c04782>.
84. Wang, G.; Du, Z.; Chen, H.; et al. Tissue-specific accumulation, depuration, and transformation of triphenyl phosphate (TPHP) in adult zebrafish (*Danio rerio*). *Environ. Sci. Technol.* **2016**, *50*, 13555–13564. <https://doi.org/10.1021/acs.est.6b04697>.
85. Yang, R.; Ye, Y.; Chen, Y.; et al. First insight into the formation of *in vivo* transformation products of 2-ethylhexyl diphenyl phosphate in zebrafish and prediction of their potential toxicities. *Environ. Sci. Technol.* **2023**, *57*, 451–462. <https://doi.org/10.1021/acs.est.2c05506>.
86. Bonnot, K.; Benoit, P.; Mamy, L.; et al. Transformation of PPCPs in the environment: Review of knowledge and classification of pathways according to parent molecule structures. *Crit. Rev. Environ. Sci. Technol.* **2023**, *53*, 47–69. <https://doi.org/10.1080/10643389.2022.2045159>.
87. Hou, M.; Fang, J.; Shi, Y.; et al. Exposure to organophosphate esters in elderly people: Relationships of OPE body burdens with indoor air and dust concentrations and food consumption. *Environ. Int.* **2021**, *157*, 106803. <https://doi.org/10.1016/j.envint.2021.106803>. Correction in *Environ. Int.* **2022**, *164*, 107270.
88. Ashley-Martin, J.; MacPherson, S.; Zhao, Z.; et al. Descriptive analysis of organophosphate ester metabolites in a Pan-Canadian pregnancy cohort. *Sci. Total Environ.* **2023**, *883*, 163327. <https://doi.org/10.1016/j.scitotenv.2023.163327>.
89. Li, M.; Yao, Y.; Wang, Y.; et al. Organophosphate ester flame retardants and plasticizers in a Chinese population: Significance of hydroxylated metabolites and implication for human exposure. *Environ. Pollut.* **2020**, *257*, 113633. <https://doi.org/10.1016/j.envpol.2019.113633>.
90. Yu, M.; Xie, C.; Chen, D.; et al. Development of MOF-808 based dispersive solid-phase extraction and ultra-high performance liquid chromatography tandem mass spectrometry for monitoring organophosphate diesters in urine. *Talanta* **2026**, *298*, 128950. <https://doi.org/10.1016/j.talanta.2025.128950>.
91. Ya, M.; Yu, N.; Zhang, Y.; et al. Biomonitoring of organophosphate triesters and diesters in human blood in Jiangsu Province, eastern China: Occurrences, associations, and suspect screening of novel metabolites. *Environ. Int.* **2019**, *131*, 105056. <https://doi.org/10.1016/j.envint.2019.105056>.
92. Cui, J.; Ge, Y.; Guo, M.; et al. Occupational exposure to traditional and emerging organophosphate esters: A comparison of levels across different sources and blood distribution. *Environ. Int.* **2024**, *194*, 109165. <https://doi.org/10.1016/j.envint.2024.109165>.
93. Zheng, G.; Schreder, E.; Dempsey, J.C.; et al. Organophosphate esters and their metabolites in breast milk from the United States: Breastfeeding is an important exposure pathway for infants. *Environ. Sci. Technol. Lett.* **2021**, *8*, 224–230. <https://doi.org/10.1021/acs.estlett.0c00916>.
94. Yao, S.; Zhang, L.; Lyu, B.; et al. Organophosphate esters and their metabolites in paired maternal serum and human milk: Occurrence, transfer efficiency, and metabolic conversion. *J. Environ. Sci.* **2026**, *162*, 42–50. <https://doi.org/10.1016/j.jes.2025.05.064>.
95. Wang, S.; Qian, J.; Zhang, B.; et al. Unveiling the occurrence and potential ecological risks of organophosphate esters in municipal wastewater treatment plants across China. *Environ. Sci. Technol.* **2023**, *57*, 1907–1918. <https://doi.org/10.1021/acs.est.2c06077>.

96. Li, X.; Yao, Y.; Zhao, M.; et al. Nontarget identification of novel organophosphorus flame retardants and plasticizers in rainfall runoffs and agricultural soils around a plastic recycling industrial park. *Environ. Sci. Technol.* **2023**, *57*, 12794–12805. <https://doi.org/10.1021/acs.est.3c02156>.
97. Chen, Y.; Wang, K.; Ge, X.; et al. Bacterial transformation products from organophosphate esters and their elevated environmental risks in soil and groundwater surrounding a chemical industrial park. *Environ. Sci. Technol.* **2026**, *60*, 9496–9507. <https://doi.org/10.1021/acs.est.5c13940>.
98. He, C.; Wang, X.; Tang, S.; et al. Concentrations of organophosphate esters and their specific metabolites in food in southeast Queensland, Australia: Is dietary exposure an important pathway of organophosphate esters and their metabolites? *Environ. Sci. Technol.* **2018**, *52*, 12765–12773. <https://doi.org/10.1021/acs.est.8b03043>.
99. Chen, X.; Zhang, N.; Li, L.; et al. A simple method for simultaneous determination of organophosphate esters and their diester metabolites in dairy products and human milk by using solid-phase extraction coupled to liquid chromatography-tandem mass spectrometry. *Anal. Bioanal. Chem.* **2022**, *414*, 4255–4265. <https://doi.org/10.1007/s00216-022-04079-3>.
100. Zhang, Q.; Liu, Y.; Li, S.; et al. Traditional and novel organophosphate esters in plastic greenhouse: Occurrence, multimedia migration, and exposure risk via vegetable consumption. *Environ. Sci. Technol.* **2024**, *58*, 13929–13939. <https://doi.org/10.1021/acs.est.4c02705>.
101. Su, G.; Crump, D.; Letcher, R.J.; et al. Rapid *in vitro* metabolism of the flame retardant triphenyl phosphate and effects on cytotoxicity and mRNA expression in chicken embryonic hepatocytes. *Environ. Sci. Technol.* **2014**, *48*, 13511–13519. <https://doi.org/10.1021/es5039547>.
102. Wang, Z.; Zhang, W.; Hu, X.; et al. Organophosphate esters inhibit enzymatic proteolysis through non-covalent interactions. *Environ. Int.* **2025**, *195*, 109256. <https://doi.org/10.1016/j.envint.2025.109256>.
103. Peng, Y.; Zheng, Y.; Shi, C.; et al. Disruption of the reproductive-metabolic-aging signaling cascade by organophosphate esters: Comparative toxicity of tris(1,3-dichloro-2-propyl) phosphate and bis(1,3-dichloro-2-propyl) phosphate in *Caenorhabditis elegans*. *Environ. Sci. Technol.* **2026**, *60*, 2930–2942. <https://doi.org/10.1021/acs.est.5c09180>.
104. Selmi-Ruby, S.; Marín-Sáez, J.; Fildier, A.; et al. *In Vivo* characterization of the toxicological properties of DPhP, one of the main degradation products of aryl phosphate esters. *Environ. Health Perspect.* **2020**, *128*, 127006. <https://doi.org/10.1289/ehp6826>.
105. Mitchell, C.A.; Reddam, A.; Dasgupta, S.; et al. Diphenyl phosphate-induced toxicity during embryonic development. *Environ. Sci. Technol.* **2019**, *53*, 3908–3916. <https://doi.org/10.1021/acs.est.8b07238>.
106. Zhang, Q.; Yu, C.; Fu, L.; et al. New insights in the endocrine disrupting effects of three primary metabolites of organophosphate flame retardants. *Environ. Sci. Technol.* **2020**, *54*, 4465–4474. <https://doi.org/10.1021/acs.est.9b07874>.
107. Noyes, P.D.; Haggard, D.E.; Gonnerman, G.D.; et al. Advanced morphological-behavioral test platform reveals neurodevelopmental defects in embryonic zebrafish exposed to comprehensive suite of halogenated and organophosphate flame retardants. *Toxicol. Sci.* **2015**, *145*, 177–195. <https://doi.org/10.1093/toxsci/kfv044>.
108. Kojima, H.; Takeuchi, S.; Van den Eede, N.; et al. Effects of primary metabolites of organophosphate flame retardants on transcriptional activity via human nuclear receptors. *Toxicol. Lett.* **2016**, *245*, 31–39. <https://doi.org/10.1016/j.toxlet.2016.01.004>.
109. Chen, R.; He, J.; Li, Y.; et al. Tricresyl phosphate inhibits fertilization in Japanese medaka (*Oryzias latipes*): Emphasizing metabolic toxicity. *Environ. Pollut.* **2022**, *297*, 118809. <https://doi.org/10.1016/j.envpol.2022.118809>.
110. Tariq, S.S.; Sardar, M.; Shafiq, M.; et al. Molecular insights into the binding of organophosphate flame retardant key metabolites with mineralocorticoid and estrogen receptors. *ACS Omega* **2025**, *10*, 20015–20025. <https://doi.org/10.1021/acsomega.5c02044>.
111. Deng, Y.; Yi, S.; Zheng, Y.; et al. Gestational exposure to tri-n-butyl phosphate induces maternal insulin resistance and glucose intolerance by antagonizing estrogen receptor alpha. *Environ. Sci. Technol.* **2026**, *60*, 8983–8996. <https://doi.org/10.1021/acs.est.5c14462>.
112. Luo, K.; Aimuzi, R.; Wang, Y.; et al. Urinary organophosphate esters metabolites, glucose homeostasis and prediabetes in adolescents. *Environ. Pollut.* **2020**, *267*, 115607. <https://doi.org/10.1016/j.envpol.2020.115607>.
113. Hu, P.; Ke, S.; Vinturache, A.; et al. Organophosphate esters, airway inflammation, and lung function among US participants: A nationally representative cross-sectional study from NHANES, 2011–2012. *Sci. Total Environ.* **2023**, *892*, 164755. <https://doi.org/10.1016/j.scitotenv.2023.164755>.
114. Nan, W.; Peng, Z.; Yi, T.; et al. Association between exposure to organophosphate esters metabolites and sarcopenia prevalence: A cross-sectional study using NHANES data. *Ecotoxicol. Environ. Saf.* **2024**, *285*, 117041. <https://doi.org/10.1016/j.ecoenv.2024.117041>.
115. Luo, D.; Liu, W.; Wu, W.; et al. Trimester-specific effects of maternal exposure to organophosphate flame retardants on offspring size at birth: A prospective cohort study in China. *J. Hazard. Mater.* **2021**, *406*, 124754. <https://doi.org/10.1016/j.jhazmat.2020.124754>.
116. Choi, Y.; Jeon, J.; Kim, S.D. Identification of biotransformation products of organophosphate ester from various aquatic species by suspect and non-target screening approach. *Water Res.* **2021**, *200*, 117201. <https://doi.org/10.1016/j.watres.2021.117201>.
117. Lao, J.Y.; Xu, S.; Zhang, K.; et al. New perspective to understand and prioritize the ecological impacts of organophosphate esters and transformation products in

- urban stormwater and sewage effluents. *Environ. Sci. Technol.* **2023**, *57*, 11656–11665. <https://doi.org/10.1021/acs.est.3c04159>.
118. Mabey, W.; Mill, T. Critical review of hydrolysis of organic compounds in water under environmental conditions. *J. Phys. Chem. Ref. Data* **1978**, *7*, 383–415. <https://doi.org/10.1063/1.555572>.
 119. Lyznicki, E.P., Jr.; Oyama, K.; Tidwell, T.T. Reactivity of organophosphates. IV. acid-catalyzed hydrolysis of triethyl phosphate: A comparison with ethyl acetate. *Can. J. Chem.* **1974**, *52*, 1066–1071. <https://doi.org/10.1139/v74-170>.
 120. Tang, C.X.; Tang, M.Q.; Wu, C.C.; et al. Organophosphate esters and their transformation products in megacity atmospheres: Size-dependent gas-particle partitioning and transformation potential. *J. Hazard. Mater.* **2025**, *494*, 138708. <https://doi.org/10.1016/j.jhazmat.2025.138708>.
 121. Liu, Y.; Liggio, J.; Harner, T.; et al. Heterogeneous OH initiated oxidation: A possible explanation for the persistence of organophosphate flame retardants in air. *Environ. Sci. Technol.* **2014**, *48*, 1041–1048. <https://doi.org/10.1021/es404515k>.
 122. Liu, Q.; Liggio, J.; Wu, D.; et al. Experimental study of OH-initiated heterogeneous oxidation of organophosphate flame retardants: Kinetics, mechanism, and toxicity. *Environ. Sci. Technol.* **2019**, *53*, 14398–14408. <https://doi.org/10.1021/acs.est.9b05327>.
 123. Zhang, Q.; Wang, Y.; Gao, M.; et al. Organophosphite antioxidants and novel organophosphate esters in dust from China: Large-scale distribution and heterogeneous phototransformation. *Environ. Sci. Technol.* **2023**, *57*, 4187–4198. <https://doi.org/10.1021/acs.est.2c08239>.
 124. Laversin, H.; El Masri, A.; Al Rashidi, M.; et al. Kinetic of the gas-phase reactions of OH radicals and Cl atoms with diethyl ethylphosphonate and triethyl phosphate. *Atmos. Environ.* **2016**, *126*, 250–257. <https://doi.org/10.1016/j.atmosenv.2015.11.057>.
 125. Aschmann, S.M.; Long, W.D.; Atkinson, R. Rate constants for the gas-phase reactions of OH radicals with dimethyl phosphonate over the temperature range of 278–351 K and for a series of other organophosphorus compounds at ~280 K. *J. Phys. Chem. A* **2008**, *112*, 4793–4799. <https://doi.org/10.1021/jp800899y>.
 126. Aschmann, S.M.; Long, W.D.; Atkinson, R. Temperature-dependent rate constants for the gas-phase reactions of OH radicals with 1,3,5-trimethylbenzene, triethyl phosphate, and a series of alkylphosphonates. *J. Phys. Chem. A* **2006**, *110*, 7393–7400. <https://doi.org/10.1021/jp061542r>.
 127. Wu, L.; Chládková, B.; Lechtenfeld, O.J.; et al. Characterizing chemical transformation of organophosphorus compounds by ¹³C and ²H stable isotope analysis. *Sci. Total Environ.* **2018**, *615*, 20–28. <https://doi.org/10.1016/j.scitotenv.2017.09.233>.
 128. Eysseric, E.; Gagnon, C.; Segura, P.A. Uncovering transformation products of four organic contaminants of concern by photodegradation experiments and analysis of real samples from a local river. *Chemosphere* **2022**, *293*, 133408. <https://doi.org/10.1016/j.chemosphere.2021.133408>.
 129. Liang, Y.; Zhou, X.; Wu, Y.; et al. Meta-omics elucidates key degraders in a bacterial tris(2-butoxyethyl) phosphate (TBOEP)-degrading enrichment culture. *Water Res.* **2023**, *233*, 119774. <https://doi.org/10.1016/j.watres.2023.119774>.
 130. Liang, Y.; Zhou, X.; Wu, Y.; et al. Rhizobiales as the key member in the synergistic tris(2-chloroethyl) phosphate (TCEP) degradation by two bacterial consortia. *Water Res.* **2022**, *218*, 118464. <https://doi.org/10.1016/j.watres.2022.118464>.
 131. Yu, Y.; Huang, W.; Tang, S.; et al. Metagenomic and enzymatic mechanisms underpinning efficient water treatment of 2-ethylhexyl diphenyl phosphate (EHDPP) by the microbial consortium 8-ZY. *Water Res.* **2025**, *275*, 123178. <https://doi.org/10.1016/j.watres.2025.123178>.
 132. Losantos, D.; Fernández-Arribas, J.; Pérez-Trujillo, M.; et al. Degradation of organophosphate flame retardants by white-rot fungi: Degradation pathways and associated toxicity. *Sci. Total Environ.* **2025**, *959*, 178260. <https://doi.org/10.1016/j.scitotenv.2024.178260>.
 133. Cheng, Y.; Zheng, X.; Jiang, Y.; et al. Key genes and microbial ecological clusters involved in organophosphate ester degradation in agricultural fields of a typical watershed in southwest China. *J. Hazard. Mater.* **2025**, *492*, 138076. <https://doi.org/10.1016/j.jhazmat.2025.138076>.
 134. Feng, M.; Zhou, J.; Yu, X.; et al. Insights into biodegradation mechanisms of triphenyl phosphate by a novel fungal isolate and its potential in bioremediation of contaminated river sediment. *J. Hazard. Mater.* **2022**, *424*, 127545. <https://doi.org/10.1016/j.jhazmat.2021.127545>.
 135. Yao, C.; Li, Y.; Li, J.; et al. Aerobic degradation of parent triisobutyl phosphate and its metabolite diisobutyl phosphate in activated sludge: Degradation pathways and degrading bacteria. *J. Hazard. Mater.* **2023**, *460*, 132380. <https://doi.org/10.1016/j.jhazmat.2023.132380>.
 136. Yu, Y.; Huang, W.; Tang, S.; et al. Degradation mechanisms of isodecyl diphenyl phosphate (IDDP) and bis-(2-ethylhexyl)-phenyl phosphate (BEHPP) using a novel microbially-enriched culture. *J. Hazard. Mater.* **2025**, *494*, 138453. <https://doi.org/10.1016/j.jhazmat.2025.138453>.
 137. Ye, J.; Tang, S.; Qiu, R.; et al. Biodegradation pathway and mechanism of tri(2-chloropropyl) phosphate by *Providencia rettgeri*. *J. Environ. Sci.* **2024**, *144*, 26–34. <https://doi.org/10.1016/j.jes.2023.07.023>.
 138. Guan, Q.; Jiang, C.; Li, Y.; et al. Biodegradation of cresyl diphenyl phosphate using microbial consortium enriched from anaerobic activated sludge. *J. Environ. Chem. Eng.* **2025**, *13*, 119610. <https://doi.org/10.1016/j.jece.2025.119610>.
 139. Zhu, X.; Deng, S.; Fang, Y.; et al. Dehalococcoides-containing enrichment cultures transform two chlorinated organophosphate esters. *Environ. Sci. Technol.* **2022**, *56*, 1951–1962. <https://doi.org/10.1021/acs.est.1c06686>.
 140. Yang, S.; Wu, J.; Wang, H.; et al. New dechlorination products and mechanisms of tris (2-chloroethyl)

- phosphate by an anaerobic enrichment culture from a vehicle dismantling site. *Environ. Pollut.* **2023**, *338*, 122704. <https://doi.org/10.1016/j.envpol.2023.122704>.
141. Yang, T.; Zhou, X.; Wu, Y.; et al. Metagenomic analyses of aerobic bacterial enrichment cultures that degraded tris(2-chloroethyl) phosphate (TCEP) and its transformation products. *Environ. Pollut.* **2024**, *361*, 124825. <https://doi.org/10.1016/j.envpol.2024.124825>.
 142. Yang, S.; Wu, J.; Yang, Q.; et al. Dechlorination of mixed chlorinated organophosphate esters (V6 and TCEP) and associated reductive dehalogenase gene expression by *Dehalococcoides mccartyi*. *Appl. Environ. Microbiol.* **2026**, *92*, e01990-25. <https://doi.org/10.1128/aem.01990-25>.
 143. Losantos, D.; Palacios, O.; Berge, M.J.; et al. Novel method for rapid monitoring of OPFRs by LLE and GC-MS as a tool for assessing biodegradation: Validation and applicability. *Anal. Bioanal. Chem.* **2024**, *416*, 1493–1504. <https://doi.org/10.1007/s00216-024-05154-7>.
 144. Wang, Q.; Zhao, H.; Bekele, T.G.; et al. Citric acid can enhance the uptake and accumulation of organophosphate esters (OPEs) in *Suaeda salsa* rhizosphere: Potential for phytoremediation. *J. Hazard. Mater.* **2023**, *443*, 130169. <https://doi.org/10.1016/j.jhazmat.2022.130169>.
 145. Yu, X.; Yao, R.; Xiao, M.; et al. Revealing novel phytotoxicity pathways in rice under two organophosphate esters exposure: From biotransformation processes to toxic intermediates and systemic metabolic perturbations. *J. Environ. Manage.* **2025**, *395*, 128011. <https://doi.org/10.1016/j.jenvman.2025.128011>.
 146. Liu, S.; Wang, G.; Xing, Z.; et al. Stable isotope and multiomics reveal uptake, translocation, and transformation mechanisms of tris(2-chloroethyl) phosphate in wheat (*Triticum aestivum* L.). *J. Agric. Food Chem.* **2024**, *72*, 27797–27807. <https://doi.org/10.1021/acs.jafc.4c08393>.
 147. Yu, Y.; Yu, X.; Zhang, D.; et al. Biotransformation of organophosphate esters by rice and rhizosphere microbiome: Multiple metabolic pathways, mechanism, and toxicity assessment. *Environ. Sci. Technol.* **2023**, *57*, 1776–1787. <https://doi.org/10.1021/acs.est.2c07796>.
 148. Yu, Y.; Ai, T.; Huang, J.; et al. Metabolism of isodecyl diphenyl phosphate in rice and microbiome system: Differential metabolic pathways and underlying mechanisms. *Environ. Pollut.* **2024**, *361*, 124803. <https://doi.org/10.1016/j.envpol.2024.124803>.
 149. Yu, Y.; Huang, J.; Jin, L.; et al. Translocation and metabolism of tricresyl phosphate in rice and microbiome system: Isomer-specific processes and overlooked metabolites. *Environ. Int.* **2023**, *172*, 107793. <https://doi.org/10.1016/j.envint.2023.107793>.
 150. Deng, Y.; Zhao, H.; Zhang, X.; et al. The dissipation of organophosphate esters mediated by ryegrass root exudate oxalic acid in soil: Analysis of enzymes activities, microorganism. *Chemosphere* **2024**, *356*, 141896. <https://doi.org/10.1016/j.chemosphere.2024.141896>.
 151. Li, J.; Zhang, Y.; Meng, W.; et al. First insight on *in vitro* metabolism of three newly identified aryl organophosphate esters via a suspect coupled with nontarget screening approach. *Toxicol. Lett.* **2021**, *348*, 73–84. <https://doi.org/10.1016/j.toxlet.2021.05.009>.
 152. Wang, L.; Huang, X.; Laserna, A.K.C.; et al. Untargeted metabolomics reveals transformation pathways and metabolic response of the earthworm *Perionyx excavatus* after exposure to triphenyl phosphate. *Sci. Rep.* **2018**, *8*, 16440. <https://doi.org/10.1038/s41598-018-34814-9>.
 153. Choi, Y.; Jeon, J.; Choi, Y.; et al. Characterizing biotransformation products and pathways of the flame retardant triphenyl phosphate in *Daphnia magna* using nontarget screening. *Sci. Total Environ.* **2020**, *708*, 135106. <https://doi.org/10.1016/j.scitotenv.2019.135106>.
 154. Wang, G.; Chen, H.; Du, Z.; et al. *In Vivo* metabolism of organophosphate flame retardants and distribution of their main metabolites in adult zebrafish. *Sci. Total Environ.* **2017**, *590–591*, 50–59. <https://doi.org/10.1016/j.scitotenv.2017.03.038>.
 155. Wu, X.; Zhu, Y.; Yang, M.; et al. Earthworms enhance the bioremediation of tris(2-butoxyethyl) phosphate-contaminated soil by releasing degrading microbes. *J. Hazard. Mater.* **2023**, *452*, 131303. <https://doi.org/10.1016/j.jhazmat.2023.131303>.
 156. Li, J.; Liu, Y.; Meng, W.; et al. Biotransformation of organophosphate diesters characterized via *in vitro* metabolism and *in vivo* screening. *Environ. Sci. Technol.* **2024**, *58*, 4381–4391. <https://doi.org/10.1021/acs.est.3c09803>.
 157. Shen, J.; Zhang, Y.; Yu, N.; et al. Organophosphate ester, 2-ethylhexyl diphenyl phosphate (EHDPP), elicits cytotoxic and transcriptomic effects in chicken embryonic hepatocytes and its biotransformation profile compared to humans. *Environ. Sci. Technol.* **2019**, *53*, 2151–2160. <https://doi.org/10.1021/acs.est.8b06246>.
 158. Xu, W.; Zhang, W.; Yu, Z.; et al. A comparative study for organophosphate triesters and diesters in mice via oral gavage exposure: Tissue distribution, excreta elimination, metabolites and toxicity. *Environ. Int.* **2024**, *193*, 109114. <https://doi.org/10.1016/j.envint.2024.109114>.
 159. Alves, A.; Erratico, C.; Lucattini, L.; et al. Mass spectrometric identification of *in vitro*-generated metabolites of two emerging organophosphate flame retardants: V6 and BDP. *Chemosphere* **2018**, *212*, 1047–1057. <https://doi.org/10.1016/j.chemosphere.2018.08.142>.
 160. Kang, P.; Chen, Q.; Wu, J.; et al. Novel organophosphate ester tris(2,4-di-tert-butylphenyl) phosphate alters lipid metabolism: Insights from lipidomic analysis and mRNA expression. *Chem. Res. Toxicol.* **2025**, *38*, 448–457. <https://doi.org/10.1021/acs.chemrestox.4c00460>.
 161. Yin, Y.; Zhao, N.; Li, Y.; et al. Deposition, bioaccumulation and depletion of organophosphate triesters (tri-OPEs) and their organophosphate diester metabolites (di-OPEs) from feed to laying hens' eggs. *J. Hazard. Mater.* **2022**, *440*, 129858. <https://doi.org/10.1016/j.jhazmat.2022.129858>.
 162. Yin, Y.; Zhao, N.; Pan, W.; et al. Unravelling bioaccumulation, depletion and metabolism of organophosphate triesters in

- laying hens: Insight of *in vivo* biotransformation assisted by diester metabolites. *J. Hazard. Mater.* **2024**, *466*, 133598. <https://doi.org/10.1016/j.jhazmat.2024.133598>.
163. Yue, C.; Ma, S.; Liu, R.; et al. Pollution profiles and human health risk assessment of atmospheric organophosphorus esters in an e-waste dismantling park and its surrounding area. *Sci. Total Environ.* **2022**, *806*, 151206. <https://doi.org/10.1016/j.scitotenv.2021.151206>.
 164. Wang, S.Q.; Hu, Z.C.; Li, J.C.; et al. Microbial interactions and health risks of organophosphate esters and their transformation products in indoor dust. *Environ. Int.* **2026**, *210*, 109333.
 165. Du, B.; Shen, M.; Chen, H.; et al. Beyond traditional organophosphate triesters: Prevalence of emerging organophosphate triesters and organophosphate diesters in indoor dust from a mega e-waste recycling industrial park in South China. *Environ. Sci. Technol.* **2020**, *54*, 12001–12012.
 166. Tan, H.; Yang, L.; Yu, Y.; et al. Co-existence of organophosphate di- and tri-esters in house dust from South China and Midwestern United States: Implications for human exposure. *Environ. Sci. Technol.* **2019**, *53*, 4784–4793.
 167. Zhao, L.; Zhu, H.; Cheng, Z.; et al. Co-occurrence and distribution of organophosphate tri- and di-esters in dust and hand wipes from an e-waste dismantling plant in central China. *Sci. Total Environ.* **2023**, *878*, 162989.
 168. Gao, M.; Wang, Y.; Wei, L.; et al. Novel organophosphate esters and their transformation products in offshore sediment from eastern China: Occurrence, temporal trend, and risk assessment. *Environ. Int.* **2025**, *195*, 109205. <https://doi.org/10.1016/j.envint.2024.109205>.
 169. Zhang, X.; Bi, Y.; Fu, M.; et al. Organophosphate tri- and diesters in source water supply and drinking water treatment systems of a metropolitan city in China. *Environ. Geochem. Health* **2023**, *45*, 2401–2414.
 170. Liang, C.; Mo, X.J.; Xie, J.F.; et al. Organophosphate tri-esters and di-esters in drinking water and surface water from the Pearl River Delta, South China: Implications for human exposure. *Environ. Pollut.* **2022**, *313*, 120150.
 171. An, R.; Wang, J.; Cao, L.; et al. Environmental risks of thermal insulation manufacturing under global decarbonization: A case study of organophosphate esters using targeted and nontargeted analyses. *Environ. Sci. Technol.* **2025**, *59*, 26157–26170. <https://doi.org/10.1021/acs.est.5c11507>.
 172. Castro-Jiménez, J.; Aminot, Y.; Bely, N.; et al. Organophosphate ester additives and microplastics in benthic compartments from the Loire estuary (French Atlantic coast). *Mar. Pollut. Bull.* **2024**, *201*, 116256. <https://doi.org/10.1016/j.marpolbul.2024.116256>.
 173. Zapata-Corella, P.; Velázquez-Gómez, M.; Pollono, C.; et al. Evaluating factors affecting the sample processing for trace analysis of organophosphate tri- and di-esters in seawater: Application in the Loire estuary (France). *Mar. Pollut. Bull.* **2026**, *222*, 118804. <https://doi.org/10.1016/j.marpolbul.2025.118804>.
 174. Zhang, L.; Xing, Y.; Zhang, P.; et al. Organophosphate triesters and their transformation products in sediments of mangrove wetlands in the Beibu Gulf, South China sea. *Molecules* **2024**, *29*, 736. <https://doi.org/10.3390/molecules29030736>.
 175. Chen, P.; Ma, S.; Yang, Y.; et al. Organophosphate flame retardants, tetrabromobisphenol a, and their transformation products in sediment of e-waste dismantling areas and the flame-retardant production base. *Ecotoxicol. Environ. Saf.* **2021**, *225*, 112717. <https://doi.org/10.1016/j.ecoenv.2021.112717>.
 176. Gao, M.; Zhang, Q.; Wu, S.; et al. Contamination status of novel organophosphate esters derived from organophosphite antioxidants in soil and the effects on soil bacterial communities. *Environ. Sci. Technol.* **2024**, *58*, 10740–10751. <https://doi.org/10.1021/acs.est.3c10611>.
 177. Tian, Y.X.; Wang, Y.; Chen, H.Y.; et al. Organophosphate esters in soils of Beijing urban parks: Occurrence, potential sources, and probabilistic health risks. *Sci. Total Environ.* **2023**, *879*, 162855. <https://doi.org/10.1016/j.scitotenv.2023.162855>.
 178. Meng, J.; Long, C.; Fang, L.; et al. National urinary metabolites of organophosphate flame retardants in urban Chinese residents. *Environ. Pollut.* **2025**, *370*, 125886. <https://doi.org/10.1016/j.envpol.2025.125886>.
 179. Wang, H.; Bian, R.; Stubbings, W.A.; et al. Human exposure to organophosphate esters (OPEs): A comparison between home and school microenvironments and inter-individual variations. *Environ. Pollut.* **2025**, *383*, 126839. <https://doi.org/10.1016/j.envpol.2025.126839>.
 180. Huang, Q.; Hou, R.; Lin, L.; et al. Bioaccumulation and trophic transfer of organophosphate flame retardants and their metabolites in the estuarine food web of the pearl river, China. *Environ. Sci. Technol.* **2023**, *57*, 3549–3561. <https://doi.org/10.1021/acs.est.2c05619>.
 181. Fu, D.; Lu, W.; Peng, C.; et al. Organophosphorus esters in edible seaweeds: Higher levels and different bioaccumulation patterns relative to terrestrial vegetables. *Food Chem.* **2026**, *501*, 147565. <https://doi.org/10.1016/j.foodchem.2025.147565>.
 182. Wang, H.; Qin, Z.; Bian, R.; et al. Single injection by LC-ESI-MS/MS for simultaneous determination of organophosphate tri- and di-esters in plant tissue based on ultrasonic-assisted sequential extraction and single-step purification. *Food Chem.* **2024**, *437*, 137917. <https://doi.org/10.1016/j.foodchem.2023.137917>.
 183. Chen, N.; Fan, S.; Zhang, N.; et al. Organophosphate esters and their diester metabolites in infant formulas and baby supplementary foods collected in Beijing, China: Occurrence and the implications for infant exposure. *Sci. Total Environ.* **2022**, *827*, 154272. <https://doi.org/10.1016/j.scitotenv.2022.154272>.
 184. Cui, X.; Yao, S.; Jia, H.; et al. Organophosphate esters and their metabolites in Beijing total diets: Occurrence, time trend, and dietary exposure assessment. *Food Chem.*

- Toxicol.* **2024**, *194*, 115103. <https://doi.org/10.1016/j.fct.2024.115103>.
185. Hou, M.; Wang, Y.; Ding, H.; et al. Nationwide investigation on organophosphate esters and di-esters in raw grains from China: Distribution, sources, and implications for risk assessment. *Environ. Int.* **2025**, *198*, 109437. <https://doi.org/10.1016/j.envint.2025.109437>.
186. Li, X.; Zhao, N.; Fu, J.; et al. Organophosphate diesters (di-OPEs) play a critical role in understanding global organophosphate esters (OPEs) in fishmeal. *Environ. Sci. Technol.* **2020**, *54*, 12130–12141. <https://doi.org/10.1021/acs.est.0c03274>.
187. Tran-Lam, T.T.; Pham, P.T.; Dao, Y.H.; et al. Organophosphate esters and their metabolites in eggs from Vietnam. *Food Addit. Contam. Part B Surveill.* **2025**, *18*, 65–77. <https://doi.org/10.1080/19393210.2024.2419588>.
188. Yao, S.; Shi, Z.; Cao, P.; et al. A global survey of organophosphate esters and their metabolites in milk: Occurrence and dietary intake via milk consumption. *J. Hazard. Mater.* **2023**, *442*, 130080. <https://doi.org/10.1016/j.jhazmat.2022.130080>.
189. Chakraborty, G.; Joshi, B.; Ahire, K.; et al. Tributyl phosphate inhibits neurogenesis and motor functions during embryonic development in zebrafish. *Aquat. Toxicol.* **2025**, *279*, 107203. <https://doi.org/10.1016/j.aquatox.2024.107203>.
190. Li, Y.; Zhao, M.; Shen, X.; et al. Adverse effects of aryl organophosphate esters on reproduction. *Environ. Sci. Technol.* **2025**, *59*, 10122–10135. <https://doi.org/10.1021/acs.est.5c01992>.
191. Fan, T.; Yan, Z.; Huang, W.; et al. A comprehensive review of contents, toxic effects, metabolisms, and environmental behaviors of brominated and organophosphorus flame retardants. *J. Hazard. Mater.* **2025**, *496*, 139428. <https://doi.org/10.1016/j.jhazmat.2025.139428>.