

From Contamination to Remediation: Understanding the Toxicity, Risk Assessment, and Degradation Pathways of Triphenyl Phosphate and Related Organophosphate Flame Retardants in Water and Soil

Vasanthiya Tej A ^{a, b}, Pranika M ^{a, b}, Adhithya S ^{a, b}, Nithya K ^{a, b*}, Asha Sathish ^c, V.Kumar ^d

^a Department of Chemical Engineering and Materials Science, Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India- 641112.

^b Centre of Excellence in Advanced Materials and Green Technologies (CoE-AMGT), Amrita School of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, India - 641112.

^c Department of Chemistry, Amrita School of Physical Sciences, Coimbatore, Amrita Vishwa Vidyapeetham, India – 641112

^d Magan Centre for Applied Mycology, Cranfield University, Cranfield, MK43 0AL, United Kingdom

*Corresponding Author Email: k_nithya@cb.amrita.edu (K. Nithya), Vinod.Kumar@cranfield.ac.uk (Vinod Kumar)

Abstract:

Triphenyl Phosphate (TPhP), a widely used organophosphate flame retardant (OPFR), has been increasingly detected in the environment via soil and water matrices, due to its persistence and potential toxicity. While numerous studies have investigated its behavior and remediation in aquatic environments, limited attention has been paid to study the TPhP occurrence and treatment in soil. This disparity is attributed to the inherent complexity and heterogeneity of soil, a dynamic matrix composed of diverse mineral particles, organic matter, and microbial populations. Unlike water, soil conditions are difficult to replicate in controlled environments, and factors such as adsorption to organic matter and restricted oxygen diffusion can significantly impede degradation processes. These limitations result in prolonged persistence and delayed remediation in terrestrial settings. This review aims to bridge the knowledge gap in OPFR remediation and promote sustainable solutions for mitigating TPhP and other OPFR-related contaminants from the environment. Remediation strategies, including biological, chemical, and substance-based natural approaches, are discussed, with an emphasis on their degradation mechanisms and removal efficiencies. Despite the limited research on TPhP degradation in aquatic environments, remediation strategies for soil and sediments remain largely unexplored, underscoring the need for further research in this area. In addition, this review explores the toxicity, global distribution, and bioaccumulation risks of TPhP and related OPFRs in both water and soil environments. The paper concludes by addressing key challenges and outlining strategic approaches and potential solutions for the effective remediation and risk management of TPhP and related OPFRs in environmental systems.

Keywords: Triphenyl phosphate, Organophosphate flame retardant, Soil, Water, Chemical, Biological, Natural-based substances

1. Introduction

In recent years, fire hazards have posed a significant concern among various industrial sectors, emphasizing the need for effective prevention measures. One such approach encompasses the incorporation of Flame retardant (FR), a chemical compound, to ensure fire safety by reducing flammability and slowing down the fire spread [1]. Mostly, FR works by physically blocking flames or chemically altering the combustion process to inhibit the ignition and flame propagation [2]. These FRs are widely used by various manufacturing industries, including plastic, textiles, furniture, transportation, construction materials, and electronics, where fire hazards are reported to be a major substantial risk [3]–[5]. In the early 1970s, poly-brominated diphenyl ethers (PBDEs) were extensively used as FRs due to their excellent flame retarding properties. However, regulations by the Stockholm Convention have levied commercial PBDE-based products due to high toxicity, bioaccumulation, and environmental persistence [6]. As a result, organophosphorus flame retardants (OPFRs) emerged as an alternative to PBDEs to ensure compliance with fire safety standards and regulations for manufacturers [7][8]. This led to an increase in the production of OPFRs such as triphenyl phosphate (TPhP), which were reported as a leading non-halogenated flame retardant, followed by international regulations on the use of halogenated compounds [9][10]. Moreover, TPhP has been classified as an Alternate Flame Retardant (AFR) and also recognized as a high-production volume chemical compound by the European Union [11].

Triphenyl phosphate (TPhP) is an OPFR belonging to the aryl-substituted class, and is chemically a tri-ester of phosphoric acid and phenol with the formula $(C_6H_5)_3PO_4$ [12]. Due to the widespread use, TPhP is frequently detected in various environmental matrices such as air, water, soil, plants, organisms, and anthropogenic residues coming from different sources via industrial and municipal waste streams [13][14]. Since TPhP is a plasticizer, it is also found in various food products due to plant uptake and accumulation [15][16], making it susceptible to long-range atmospheric transport, leading towards global dispersion in remote areas. Although TPhP is considered an alternative to brominated flame retardants (BFR), various studies report that it may be more toxic than other halogenated-free flame retardants, leading to concerns about its environmental persistence, toxicity, and potential health risks [17][18].

Through various studies [19]–[23], the presence of TPhP in the environment is often detected in surface waters and sediments. TPhP is a hydrophobic compound with the potential to bioaccumulate in aquatic organisms and exhibit endocrine-disrupting effects, raising environmental and ecological concerns [24][25]. Studies have proven that TPhP possesses the ability to inhibit the hormonal system of marine organisms [26], leading to the development of reproductive problems upon exposure [27]. Moreover, TPhP presence has been found to leach from consumer products like personal care items [28], automotive components, electronic materials [29], and so on. This leaching process further exacerbates environmental contamination, particularly in the water systems, by entering the domestic wastewater streams [30][31].

On the other hand, soil contamination with TPhP is another environmental concern that arises through various pathways, including industrial effluent from the plastic, electronic, and automotive industries. In addition, TPhP can also enter into the soil via atmospheric deposition, and agricultural practices, particularly through pesticides, fertilizers, or plastic materials used in farming [32]. The research on TPhP indicates that its chemical properties enable it to adsorb onto soil particles, making it persistent in the environment. The key chemical properties of TPhP include – log Kow (octanol-water partition coefficient) 4.59, moderate water solubility 2.0 mg/L, pKa ~0.98, and partitioning coefficient, enabling it to accumulate in the soil [18][33][34]. The accumulation of TPhP in soil can cause a potential risk to

microorganisms, leading to alteration of microbial diversity and enzymatic activities. This, in turn, negatively inhibits the soil health and nutrient cycling abilities of microorganisms, leading to an increase in contamination levels and ecological impact [35]–[38].

Recent reviews [39]–[43], highlights the need for a deeper understanding on the environmental and health impacts of TPhP. Various studies have demonstrated that industrial exposure to TPhP concentrations between 3-5 mg/m³ can lead to respiratory irritation, neurotoxicity, or endocrine disruption [44][45]. Meanwhile, to mitigate the environmental risks associated with TPhP contamination, regulatory guidelines have established permissible limits to ensure ecosystem safety. The World Health Organization (WHO) has not established a guideline value for TPhP in drinking water. However, the European Chemicals Agency (ECHA) recommends a predicted no-effect concentration (PNEC) of 0.48 µg/L (480 ng/L) for freshwater environments to protect aquatic organisms. Similarly, for terrestrial environments, ECHA has proposed a PNEC for soil of 0.028 mg/kg dry weight (28 µg/kg), which is considered protective for soil-dwelling organisms [46].

This review paper provides a comprehensive assessment of TPhP and other OPFR contamination in soil and water, with particular focus on its risk assessment, toxicity, and degradation studies, based on the existing literature. Notably, this is the first review that predominantly explores the TPhP and other OPFR mitigation in soil using chemical agents, microorganisms, and natural-based substances. The review is structured in two major phases to enhance clarity and understanding. In the first phase, the occurrence, distribution, and environmental fate of TPhP are examined, followed by a detailed account of its toxicological impacts on aquatic and terrestrial ecosystems. In the second phase, various remediation strategies are critically discussed, including chemical-assisted processes, biological methods, and nature-based approaches. This is followed by a specific focus on soil remediation challenges, highlighting the knowledge gap in terrestrial systems. Additionally, the review presents recent advances in analytical detection techniques for monitoring TPhP in environmental matrices. Finally, the paper concludes with insights into monitoring and regulatory measures for detecting TPhP across various environmental systems using advanced analytical techniques. By compiling recent findings on TPhP remediation, this review aims to bridge knowledge gaps and further illustrate the need for future research and contributions towards the development of a sustainable environment. By organizing the review in this way, we aim to improve readability and provide a systematic understanding of TPhP pollution and its management.

2. Search Strategy and Methodology

A systematic review of Triphenyl phosphate (TPhP) and organophosphate flame retardants (OPFRs) remediation from environmental matrices such as soil and water, published between 2014 and 2025, was conducted using a mixed-methods approach. Peer-reviewed articles were selected from the various scientific database, which typically includes Scopus, Web of Science, ScienceDirect, and Google Scholar. The articles selected from the database were filtered based on title, abstract, and full-text screening by defined inclusion and exclusion criteria. Only studies published in English that focused on the environmental occurrence, toxicity, degradation, and remediation of TPhP/OPFRs were included. At the initial stage, a total of 724 papers were identified across all database of which 331 duplicate records were removed, followed by 393 relevant articles. Further, the obtained 393 papers were subjected to a second round of screening, where non-relevant articles were excluded based on the absence of a specific focus on OPFRs in environmental matrices like soil and water. Excluding all the other papers, 147 papers were included in this review paper. To ensure transparency, the review process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)

outdoor spaces such as parks (320 pg/m³) [59][65][66]. This presence can be linked to the use of TPhP as a plasticizer in PVC, thermoplastics, synthetic rubber, and cellulosic polymers, as well as its application as a lubricant in hydraulic fluids. For instance, TPhP concentration was found to range from as low as 0.0004 mg/kg from a park area in Guangzhou, China [65] to as high as 170 mg/kg from car dust in the United Kingdom.

In general, TPhP is slowly released into the environmental matrices throughout its lifecycle during production, usage, or disposal by various mechanisms such as volatilization, abrasion, and leaching. Due to its varying physical and chemical properties, it can be transported across different environmental media (soil, water & air) and has been detected in multiple environmental compartments [67].

3.1 Toxicity effect of TPhP in Soil

The release of TPhP into soil occurs through multiple pathways. Leaching at landfill sites containing TPhP is the primary cause for the prominent presence of TPhP in soil [68]. Other pathways include irrigation with wastewater or river water, industrial runoff, disposal of sewage sludge, wet and dry deposition, and atmospheric transport along with particulate matter and precipitate in soil [69] [70]. It is frequently detected in urban and agricultural soil, including park areas (0.004 mg/kg) [65], paddy and vegetable fields (0.005 mg/kg, dry wt) [65], commercial areas (0.046 mg/kg, dry wt) [65], roads (0.014 mg/kg, dry wt) [65], residential areas (0.009 mg/kg, dry wt) [65], open (303 ng/g, dry wt) and closed recycling sites (48.4 ng/g, dry wt) [66] farmlands (8.33 ng/g, dry wt) [66] etc.

At these environmental concentrations, TPhP can negatively impact soil ecosystems. Studies have shown that OPFRs like TPhP can alter soil microbial community structure and reduce key enzyme activities, including dehydrogenase and urease, which are essential for organic matter decomposition and nutrient cycling. These disruptions can diminish soil respiration and nitrogen transformation processes, ultimately depleting soil fertility and impairing plant growth [71]. Therefore, investigating the soil toxicity of OPFRs such as TPhP is critical for understanding their long-term ecological and agricultural implications.

3.2 Toxicity Effect of TPhP in Water

Water systems also serve as significant sinks for TPhP contamination. The concentration ranges from 0.05 ng/L in barrelled water found in Eastern China [76] to 40.5 ng/L in drinking water found in South Korea [58] where the consumption of OPFR increased from 4% to 11%. TPhP was also reported to be found in various sources of water, such as lakes [72], tap [73], filtered [73] Well, bottled and barrelled water, etc. TPhP enters the aquatic environment mainly via hydraulic fluid leakages, leaching, and volatilization from plastics [18][48] through effluent discharge from various sources, such as sewage treatment plants [74][75][76][77][78], discharge of leachate in landfills [74][79][80], centralized solid waste treatment plants, and uncontrolled discharge from industries and daily life activities [74][81]. Research by Khan et al [82] proved that leakage of FRs in pipelines and leaching into shallow groundwater is also the reason for the contamination of potable water with FRs. Many studies have reported that water discharged from WWTPs is also a source of TPhP contamination in natural waterbodies [83]. Apart from this, TPhP is also found in sediments of the river and seawater at relatively lower concentrations [72][84] [85] depending on the urban and industrial activities near the catchment areas [86].

Although TPhP concentrations in aquatic systems are relatively low (ng/L), toxicological studies demonstrate that even at these levels, chronic exposure can induce oxidative stress, neurotoxicity, endocrine disruption, and reproductive impairment. For example, zebrafish embryos showed delayed

hatching and oxidative stress at 10–100 µg/L TPhP [87]; *Daphnia magna* exposed to low µg/L exhibited reduced reproduction and metabolic stress [88]; and rotifers experienced disturbances in lipid metabolism and food web dynamics at 1 mg/L [89]. These effects raise concerns about long-term ecological implications even at environmentally relevant concentrations.

3.3. Toxicity effect of TPhP in Biota

Besides water & soil, the toxicity effects of TPhP on aquatic and terrestrial biota have also been well documented. The toxic effects of TPhP and other OPFRs on aquatic ecosystems are summarized in Table 1. Numerous studies were published to highlight the contamination of various OPFRs in aquatic environments. Though TPhP is found to be in lesser concentration than most OPFRs, its potentially toxic effects are high, and therefore, its remediation strategies and further improvements in the same must not be overlooked. TPhP exhibited varying degrees of toxicity to aquatic organisms. It has been shown that the exposure of TPhP in different biota leads to hormonal interference with affected organisms, impairs growth, and reproduction. For instance, zebrafish (*Danio rerio*) embryos exposed to TPhP at concentrations as low as 10–100 ng/L experienced delayed hatching, abnormal development, and alterations in gene expression related to hormone regulation [90]. In *Daphnia magna*, sublethal exposure to TPhP resulted in reduced reproductive output, elevated oxidative stress biomarkers, and disrupted molting cycles [88]. Similarly, in benthic organisms and aquatic plants, TPhP has been reported to bioaccumulate and interfere with metabolic enzymes, potentially affecting population dynamics and trophic transfer [91].

These findings suggest that even low concentrations of TPhP in the environment can have profound effects on aquatic and terrestrial biota, particularly through chronic exposure. Therefore, its ecotoxicological risks should not be underestimated, and its regulation and removal from contaminated systems remain a priority.

3.4 Toxicity effect of TPhP in air

Understanding the occurrence of TPhP in the air is crucial to comprehend its eventual distribution in soil and water, as the atmosphere often acts as a transport medium. TPhP can be released into the air from various sources such as flame retardants, plasticizers, and e-waste processing, and due to its low vapor pressure and strong affinity for particles, it often exists as particulate matter. These airborne particles can travel long distances before settling onto soil and water bodies through dry or wet deposition, leading to widespread environmental contamination. In the presence of nitrogen and sulfur oxides, TPhP was found to degrade to DPhP and OH-DPhP, which have also been proven to be toxic [56]. A large percentage of TPhP is emitted via air and exists as particulate matter due to its low vapor pressure and high partition coefficients [92]. Additionally, the presence of TPhP in remote areas of the world is attributed to its long-range transport [86]. Contamination levels are found to be higher in areas near flame-retardant manufacturing and e-waste disposal sites.

Typically, **Table 1** summarizes the toxic effects of TPhP and other OPFRs in soil, air, biota, and water ecosystems. In contrast to aquatic environments, TPhP was comparatively found in higher concentrations in soil. The table also highlights the presence of other toxic OPFRs, which are commonly found in the soil environment along with TPhP. Soil and water play an important role in the fate of TPhP and other OPFRs, as they influence decomposition by microbes and dry and wet decomposition from the atmosphere [13][93]. Since TPhP is an aromatic OPFR, it has a higher potential to associate with soil and biota components than aliphatic OPFRs [69].

Furthermore, studies also report that OPFRs may leach into food due to plant uptake and accumulation, thus, there is a risk of dietary exposure and, thereby, potential health effects, which might include endocrine-disrupting activities and neurodevelopmental effects. The concentration of OPFR in these various matrices must be quantified using holistic assessments that involve very sensitive methods of analytical analysis, such as LC-MS/MS, to inform risk assessments and guide public health policies for the mitigation of exposure.

Table 1. Toxicity Effects of OPFRs in Various Environmental Matrices

	Contaminants	Concentration	Toxicity Level	Effect	Reference
Toxicity effects of TPhP and some other OPFRs in water	TPhP	12.5 µg/L	High	Decreased α -diversity of fish gut microbiome	[94]
	TCEP	0.5 - 10 µg/L	Moderate	Neurotoxicity and developmental toxicity in zebrafish	[65]
	TDCPP	1.2 µg/L	High	Endocrine disruption in aquatic organisms	[83]
Toxicity effects of TPhP and other OPFRs in soil	TPhP	4900 ng/g	High	Endocrine Disruption, Neurotoxicity	[94]
	TCEP	1200 ng/g	Moderate	Altered microbial communities	[83]
	TDCPP	900 ng/g	High	Developmental toxicity in soil invertebrates	[83]
Toxicity effects of TPhP and some other OPFRs in Biota	TPhP	3.2 µg/g (fish tissue)	High	Bioaccumulation, immune dysfunction	[94]
	TCEP	0.8 µg/g	Moderate	Neurotoxicity in aquatic species	[4]
	TDCPP	2.1 µg/g	High	Reproductive toxicity in fish	[83]
Toxicity effects of TPhP and some OPFRs in air	TPhP	1500 ng/g (Dust)	High	Hormonal disruption in humans	[83]
	TCEP	200 ng/m ³ (Air)	Moderate	Respiratory irritation, potential carcinogenicity	[83]
	TDCPP	700 ng/g (Sediment)	High	Persistent environmental contamination	[95]

4. Remediation in water

4.1 Chemical-assisted TPhP water remediation

Chemical-assisted methods for pollutant removal can be broadly classified into adsorption and degradation processes. Among these, adsorption is a simple, effective, and cost-effective approach widely used to remove pollutants from water [96]. This process involves immobilizing pollutants like TPhP on the surface of the adsorbent by reducing their mobility and bioavailability without changing their chemical properties [97]. In contrast to adsorption, the degradation process can effectively break down TPhP and other OPFR into less toxic compounds by reducing their persistence and environmental toxicity [98]. Some of the most effective degradation processes involve electrochemical degradation, advanced oxidation processes (AOPs), and photodegradation [99][100]. Among these, AOPs have shown superior efficiency in destroying and mineralizing TPhP due to their ability to generate reactive oxygen species (ROS) that can completely break down organic pollutants. These ROS are typically produced through the activation of various oxidants such as hydrogen peroxide (H_2O_2), peroxymonosulfate (PMS), persulfate (PS), peroxydisulfate (PDS), and bisulfite (BS) [101]–[104]. Due to AOPs' high redox potentials, both hydroxyl radicals ($E^\circ = 1.9 - 2.7 \text{ V}$) and sulfate ($E^\circ = 2.5 - 3.1 \text{ V}$) serve as the primary oxidative species in AOPs for the removal of TPhP [105]. Among them, sulfate radicals are considered more advantageous owing to their higher redox potential, greater selectivity, and longer half-life. As a result, persulfate (PS), a common precursor for sulfate radicals, has been widely adopted in practical applications such as wastewater treatment and groundwater remediation, primarily due to its excellent stability and high solubility [106]. To enhance its oxidative efficiency, PS can be activated through various methods, including UV light, transition metals, carbon-based materials, and thermal energy.

For instance, Ferrous (Fe^{2+}) ion activation, a transition metal-based activation method, is widely recognized for TPhP removal due to its lower energy requirement ($\pm 62 \text{ kJ/mol}$), cost-effectiveness, natural abundance, and environment-friendly. These attributes make it a promising approach for advanced oxidation processes. On the other hand, Yan et al [101] studied the degradation process of TPhP by Fenton reagent and Fe^{2+} /PS. Due to TPhP's stable structure, using H_2O_2 or PS alone was insufficient to achieve effective degradation. However, Fe^{2+} was found to activate H_2O_2 (via the Fenton process) to produce hydroxyl radicals and, similarly, activate PS (via the Fe^{2+} /PS process) to generate sulfate radicals. Increasing the Fe^{2+} dosage resulted in increased degradation efficiency and was applicable for a wide range of pH [105].

Since Fe^{2+} is easily oxidized to Fe^{3+} , it can lose its catalytic activity, quench sulfate radicals if present in excess, and compete with electrons, which reduces efficiency. However, nZVI (nano zerovalent iron) can gradually release Fe^{2+} and maintain a stable concentration, making it a better alternative for Fe^{2+} in activating bisulfite for TPhP removal [102]. Another method for activating PS, as elucidated by Li et al. [106], involves the use of biochar coated with nZVI. It is inferred that biochar-based composites with nano-metal particles synergize the adsorption and degradation of organic pollutants. It is to be noted that optimal conditions nZVI coated with biochar synthesized at 800°C yielded superior results in the remediation of TPhP when used to activate PS with a high catalytic degradation kinetic rate as shown in **Fig.2**. Apart from PS, PMS and PDS have also been used to generate sulfate and hydroxyl radicals. PMS is more cost-efficient, requires low energy input, and could be activated by Co^{2+} . This opens yet another opportunity for the degradation of TPhP.

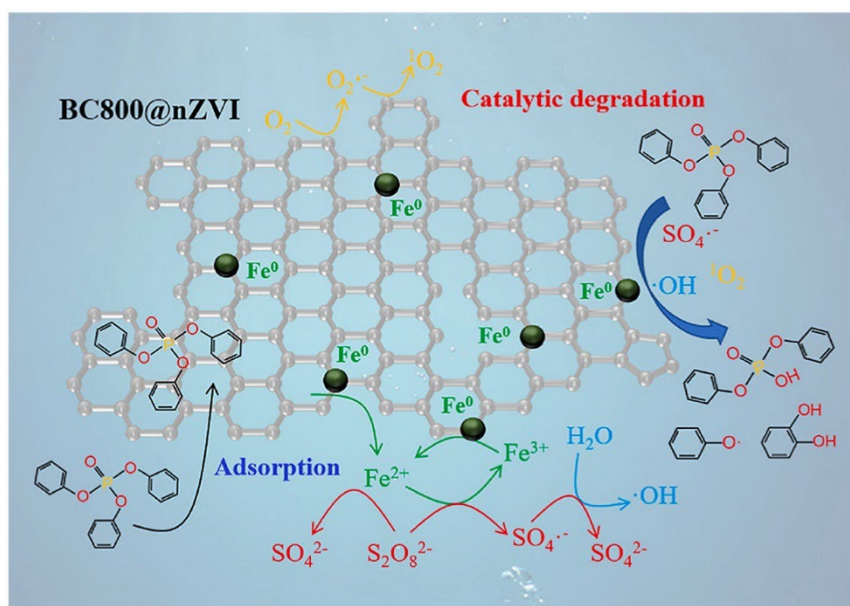


Fig.2. Schematic representation of TPhP removal via adsorption and catalytic degradation using BC800@nZVI nanocomposite (Reproduced with permission from Li et al., [106])

Song et al [107] utilized CoFe_2O_4 as a catalyst to activate PMS due to its high reusability potential by investigating its degradation pathway, kinetics, and mechanisms. Interestingly, TPhP degradation was achieved only by $\text{CoFe}_2\text{O}_4/\text{PMS}$, while no significant degradation was observed either with $\text{CoFe}_2\text{O}_4/\text{PS}$ or $\text{CoFe}_2\text{O}_4/\text{H}_2\text{O}_2$. Further, a recent study by Yu et al [108] revealed that TPhP could be degraded by the PDS alone system at a slower rate. Whereas, biochar-goethite composite pyrolyzed at 800 °C significantly enhanced the PDS activation, resulting in the accelerated degradation of TPhP due to the generation of ROS. This eminent degradation is mainly due to the breakage of phosphorus, phenoxy, and hydroxylation reaction processes. Therefore, the synergistic effect of biochar-geolite improved electron transfer efficiency by boosting catalytic activity and promoting the degradation process. In another study, Tang et al [109] designed an electrochemical AOP for the degradation of aromatic OPFRs and reported that hydroxyl is the primary ROS responsible for the degradation of TPhP.

Further, the use of transition metals to activate reactions can lead to secondary pollution, incomplete oxidation, and prolonged reaction time. Meanwhile, Valizadeh et al., [110] proposed a study on the supercritical water oxidation (SCWO) process for the effective remediation of organic pollutants into CO_2 , H_2O , N_2 , and other inorganic salts via hydroxylation, ring cleavage, and mineralization of aryl organophosphates. As a result, TPhP is degraded into hydroxylated products through radical addition and C-O bond cleavage.

The use of transition metals to activate reactions presents several drawbacks, including the potential for secondary pollution, incomplete oxidation, and prolonged reaction times. As a more effective remediation strategy, supercritical water oxidation (SCWO) offers the advantage of completely mineralizing organic pollutants into CO_2 , H_2O , N_2 , and other inorganic salts. This study reports hydroxylation, aromatic ring cleavage, and mineralization of aryl organophosphates. Specifically, TPhP undergoes degradation into hydroxylated products through radical addition and C-O bond cleavage [110].

While degradation methods are effective, adsorption remains a primary approach due to its simplicity and cost-effectiveness. However, only limited research is reported on removing TPhP via different

adsorbents. This is due to its hydrophobic nature, low water solubility, and the lack of highly selective adsorbents. Besides the limited research in this domain, a study conducted by Wang et al., [111] utilized powdered activated carbon (PAC) to remove 90% of TPhP from water sources, outperforming granulated activated carbon (GAC). This performance of PAC was attributed to differences in intraparticle diffusion rate and surface area of the material. Subsequently, the same research group reported a study using non-ionic resins XAD4 (styrene divinylbenzene) and XAD7hP (acrylic ester) to remove TPhP. The finding revealed that XAD4 showed a maximum adsorption capacity of 2.25 mmol/g, while XAD7hP exhibits less adsorption capacity of 1.12 mmol/g. These changes in the adsorption capacity of non-ionic resins revealed that XAD4 holds higher hydrophobicity and specific surface area compared to XAD7HP [103].

In another instance, Hao et al [112] synthesized a urea-functionalized $\text{Fe}_3\text{O}_4@\text{LDH}$ adsorbent targeting TPhP, and compared the performance efficiency with Urea- $\text{Fe}_3\text{O}_4@\text{SiO}_2$ and Urea- $\text{Fe}_3\text{O}_4@\text{C}$. TPhP removal by urea-functionalized $\text{Fe}_3\text{O}_4@\text{LDH}$ adsorbent achieved 589 mg/g of adsorption capacity at a pH of 5.5. Significantly, the removal efficiency of urea-functionalized $\text{Fe}_3\text{O}_4@\text{LDH}$ adsorbent is found to be higher when compared with Urea- $\text{Fe}_3\text{O}_4@\text{SiO}_2$ and Urea- $\text{Fe}_3\text{O}_4@\text{C}$.

In summary, both adsorption and degradation methods offer a promising strategy for TPhP remediation in water systems. The choice between these methods depends on factors such as cost, efficiency, and environmental impact. Therefore, adsorption remains a practical and cost-effective approach for large-scale applications while degradation techniques demonstrate high efficiency in breaking down pollutants. Various studies focused on TPhP remediation using chemical substances are discussed in **Table 2**.

Table 2. Overview of OPFRs TPhP remediation process in soil and water systems

S. No	Source	Technology	Materials	Class	Contaminants	Efficiency	Ref
1	Synthetic OPFR solution	Adsorption	Coal-based AC	Activated carbon	OPFR	Sorption capacity = 1.52 mmol/g	[111]
2	Synthetic TPhP solution	Adsorption	Carbon nanotubes	Nanomaterials	OPFR	Monolayer sorption capacity: MWCNT- 68 mg/g O-MWCNT- 87.1 mg/g SWCNT - 351.5 mg/g O-SWCNT-360.6 mg/g	[132]
3	Synthetic OPFR solution	Adsorption	Styrene divinylbenzene, acrylic ester	Non-ionic resins	OPFR	Maximum adsorption capacity XAD4 = 2.25 mmol/g XAD7hP = 1.12 mmol/g	[103]
4	Synthetic OPE solution	Adsorption	Ligand functionalized MIL-101(Fe)	Metal-organic framework	OPFR	Maximum adsorption capacity = 60 micromole/g	[133]
5	Synthetic TPhP solution	Adsorption	Urea functionalized	Layered Double Hydrides	TPhP	Maximum adsorption capacity = 589 mg/g	[134]

			Fe ₃ O ₄ @LDH				
6	Synthetic OPE solution	Adsorption	Waste Baijiu distiller's grain-based biochar	Biochar	OPFR	Maximum adsorption capacity = 752.95 mg/g	[135]
7	Synthetic TPhP solution	Adsorption	Biochar-coated nZVI activating persulfate	Advanced oxidation process	OPFR	96.9% removal efficiency with catalytic degradation Kinetic rate of 0.0484 min ⁻¹	[106]
8	Synthetic TPhP solution	Biodegradation	Activated sludge	A2O	OPFR	DT50 (time required to remove 50% of the initial concentration): Living sludge = 2.8 days, sterile sludge = 8 days. Complete removal: Living sludge = 7 d, sterile sludge = 28 d	[136]
9	Synthetic sewage	Biodegradation	Activated sludge	A2O	OPFR	Removal efficiency between 65.5% - 75.1%	[137]
10	Synthetic OPE solution	Biodegradation	Aerobic sludge culture	Activated sludge	Non-halogenated OPFR	Removal efficiency = 27 - 79%	[113]
11	Water-sediment system	Biodegradation	Sphingopyxis sp. GY	Bacteria	TPhP	Complete degradation in 36 h	[115]
12	TPhP in methanol or acetonitrile stock solution	Biodegradation	Sphingobium yanoikuyae YC-XJ2	Bacteria	Aryl-OPFR	99% degradation within 24 h	[114]
13	Synthetic TPhP solution	Biodegradation	Rhodococcus pyridinivorans YC-MTN	Bacteria	Aryl-OPFR	76.15% degradation (pH 7, 3 days, temp range of 25-45 °C)	[106]
14	TPhP in acetone	Biodegradation	APE-degrading bacterial strain YS-57	Bacteria	Aryl-OPE	Temperature = 30°C, pH = 7.0, Removal=95.6% in 4 days	[116]
15	TPhP in methanol	Biodegradation	Rhodococcus - Sphingopyxis	Bacterial consortium	Aryl-OPFR	50% degradation in 4.53 days (pH 8, 35 °C, and 0% salinity)	[118]
16	Water-sediment system	Biodegradation	Pycnoporus sanguineus	White rot fungi	TPhP	62.84% biodegradation efficiency (5 mg/L of TPhP, pH 6, 5 g/L of glucose)	[121]
17	River sediment	Biodegradation	Aspergillus sydowii FJH-1	Fungal strain	TPhP	90% efficiency within 6 days (pH 4-9, 30 °C, less than 20 mg/L of initial concentration)	[120]

18	TPhP in methanol	Biodegradation	<i>Brevibacillus brevis</i>	Bacteria	TPhP	92.1% (3 micro mol/L TPhP, pH 7, 30 °C)	[138]
19	Simulated and river water contaminated with TPhP	Bioaugmentation	<i>Brevibacillus brevis</i>	Bacteria	TPhP	97.9% after 96 h incubation	[139]
20	Synthetic TPhP solution	Biodegradation	<i>Chlorella vulgaris</i> and <i>Scenedesmus obliquus</i>	Microalgae	TPhP	64.9% in 5 days	[122]
21	TPhP in methanol	Biodegradation	<i>Pseudarthrobacter</i> and <i>Sphingopyx</i>	Bacterial consortium	TPhP	92.2% within 4 h (pH 7, inoculum size 1 g/L wet weight, 30 °C, TPhP initial concentration of 3)	[117]
22	TPhP in HSHN	Biodegradation	Water hyacinth (<i>Eichhornia crassipes</i>)	Phytoremediation	OPFR	Root concentration factor (RCF, Croot/C exposed): 6.66 - 53.6 L/kg	[123]
23	Dewatered sewage sludge	Biodegradation	<i>Flavobacterium</i> , <i>Bacillus</i> , <i>Alcaligenes</i> , <i>Pseudomonas</i> , and <i>Bacillus megaterium</i>	Aerobic and anaerobic treatment along with bacterial composition	OPFR	Removal rate T1=11.7, T2=7.07, T3=14.2, T4=1.14	[128]
24	Freshwater and seawater	Biodegradation	<i>Rhodococcus pyridinivorans</i> YC-MTN	Bacterial strain	aryl-OPFRs	TPhP removal: 92.10%	[119]
25	TPhP in DMSO	Biodegradation	Algal extracellular polymeric substances	Algae	TPhP	TPP (0.05, 0.5, and 5 mg/L) in pristine	[140]
26	Synthetic TPhP solution	Biochemical degradation	Biochar-goethite composite and persulfate system	Advanced oxidation process	TPhP	90% within 8 h (10 mM PDS conc, 30 °C, 6.12 pH)	[108]
27	Synthetic TPhP solution	Bioelectrochemical degradation	<i>Azospirillum</i> , <i>Petrimonas</i> , <i>Pseudomonas</i> and <i>Geobacter</i>	Bioelectrochemical system	TPhP	80% degradation in 480 hr (sodium acetate 1.0 g/L, TPhP 1.5 mg/L, pH 7, external voltage 0.2 V)	[141]
28	TPhP contaminated seawater, municipal wastewater, river water and tap water	Chemical degradation	Fe-activated hydrogen peroxide and persulfate	Advanced oxidation process	TPhP	Fenton=90.8%, PS=72.4%	[105]

29	Water and 5% acetone as co-solvent	Chemical degradation	Nanoscale zerovalent iron (nZVI) activated bisulfite	Sulfate radical-based advanced oxidation process	TPhP	98.2% degradation efficiency (0.5 mM nZVI and 2.0 mM bisulfite, pH 3.0)	[102]
30	TPhP in acetonitrile	Chemical degradation	CoFe ₂ O ₄ -activated peroxymonosulfate	Advanced oxidation process	TPhP	99.5% (initial pH of 7.0, 10 μ M TPhP with 0.25 g/L CoFe ₂ O ₄ and 0.5 mM PMS after 6 min oxidation)	[107]
31	Milli-Q water, humic acid solution and municipal secondary effluent spiked with OPE	Chemical degradation	Ozone and UV activated hydrogen peroxide	Advanced oxidation process	OPFR	Ozone= 70%, UV/H ₂ O ₂ = 100% within 15 min	[104]
32	Water (Milli-Q water, Milli-Q water + humic acid and river water) spiked with OPFR simultaneously	Chemical degradation	Natural sunlight, simulated sunlight and UV-C irradiation	Photodegradation	OPFR	75% of degradation after 60 min radiation exposure (in Milli-Q water)	[142]
33	Sediment contaminated with TPhP in a controlled environment	Electrochemical degradation	Anode - Ti/SnO ₂ -Sb/La-PbO ₂ , cathode - two Ti plates	Electrochemical advanced oxidation process	Aromatic OPFR	Removal efficiency of TPhP 93.70%	[143]
34	Soil	Sorption	rice straw-based pyrochar and hydrochar	Biochar	OPFR	Adsorption capacity of 9 mg/g (pH 7, 600 °C, pyrochar)	[69]
35	Simulated soil environment	Adsorption	Microplastics and soil organic matter	Microplastics	TPhP	The adsorption capacity of 0.1609 micro g/g in soil-only, 0.1966 in soil+PP-MPs, 0.3962 in soil+PS-MPs and 0.3547 in soil-EVA-MPs system	[124]
36	Soil	Biodegradation	Ryegrass root exudate oxalic acid	Phytoremediation	OPFR	64.81% dissipation rate in 30 days	[144]
37	Soil/water	Biodegradation	Biochar/aerobic composting	Sewage sludge	OPFR	49.6% degradation rate in 5% biochar	[129]

38	Soil waste	Biodegradation	Leachate from sea-based solid waste disposal site	Aerobic and anaerobic condition	OPFR	100% degradation in 50 days	[79]
39	Simulated soil environment	Chemical degradation	Peroxydisulfate	Advanced oxidation process	TPhP	70% removal in 2g soil	[126]
40	Soil	Chemical degradation	Fe-based peroxy disulfate activation	Advanced oxidation process	OPFR	62.4% degradation in 200 mM PDS concentration	[125]
41	Soil	Chemical degradation	Persulfate	Advanced oxidation process	TPhP	21.9% in soil-PS system and (69-97%) in heat-soil-PS system	[145]
42	Soil	Complexation and reduction	Peroxydisulfate	In-situ chemical oxidation	TPhP	58.6% degradation in the presence of 40 mM tea polyphenols	[127]

From the analysis of reported studies shown in **Table 2**, it is evident that the performance of AOPs in TPhP remediation is highly dependent on reaction parameters such as pH, oxidant dosage, catalyst concentration, and matrix complexity. For instance, Fe²⁺/PS systems operate best in mildly acidic conditions, while biochar-nZVI composites show broader pH compatibility with improved reusability. Though sulfate radical-based processes outperform hydroxyl radical-based systems in stability and selectivity, they often require advanced material synthesis. Compared to biological methods, chemical oxidation processes demonstrate faster kinetics and deeper mineralization but may face limitations related to secondary pollution and cost. Therefore, while AOPs offer high efficiency, their field application requires careful balance between performance, environmental impact, and material sustainability.

4.2 Remediation using microorganisms and natural-based substances:

Besides chemical methods, microorganisms and natural-based substances have also shown remarkable potential in the degradation of TPhP through various biochemical pathways. Several studies have explored the potential of microbes like bacteria, fungi, and microalgae for the removal of TPhP. Further, plant-based systems also play a main role in mitigating TPhP contamination, offering promising alternatives to conventional physicochemical methods. A study by Hou et al [113] demonstrated that enriched microbial culture from activated sludge effectively degraded non-halogenated OPFR around 29.3–89.9% over 5 cycles (25 days) of cultivation under aerobic conditions. Specific bacterial genera found from the activated sludge include- *Acinetobacter*, *Pseudomonas*, and *Bacillus*. Further, it was reported that this degradation process follows a first-order kinetics model, with TPhP exhibiting the fastest degradation rate having a half-life ranging between 12.8-99.0 h, followed by TBOEP (Tris(2-butoxyethyl) phosphate) and TNBP (Tributyl phosphate). However, key findings obtained from this study illustrate that hydrolysis, hydroxylation, methoxylation, and substitution are the dominant biotransformation pathways that act in the degradation of toxic OPFR. Similarly, Jurgens et al [26] experimented with activated sludge to determine the mineralization and primary biodegradation process

of aromatic OPFRs TPhP, PBDPP (Tris(1,3-dichloro-2-propyl) phosphate), and BPA-BDPP (Bisphenol A bis (diphenyl phosphate)). The findings revealed that TPhP was rapidly biodegraded and mineralized within 7 days, achieving 60% theoretical maximum mineralization. In contrast, PBDPP experienced rapid biodegradation with slow mineralization, whereas, BPA-BDPP was relatively slow in both biodegradation and mineralization processes. On the other hand, Hou et al [28] conducted a study using a three-electrode single-chamber bio-electrochemical system (BES) to degrade TPhP. The experimental analysis proved that the bacterial metabolism of TPhP was enhanced by applying a micro-electrical field, showcasing 85.8% of TPhP removal within 48 hours.

A novel approach to degrade TPhP was presented by Li et al [114], who isolated a halotolerant bacterium *Sphingobium yanoikuyae* YC-XJ2, with ability to degrade aryl-OPFR. The genomic analysis on *S. yanoikuyae* YC-XJ2, revealed the presence of the gene *sy-pte*, encoding phosphotriesterase enzyme. This enzyme was subsequently cloned into xx for the degradation of TPhP through a phosphotriesterase-mediated hydrolysis process by breaking the aryl phosphate structure into less toxic and biodegradable compounds. Likewise, a study by Yu et al [115] revealed that *Sphingopyxis* sp. GY, an Alphaproteobacteria, was able to degrade 100% of 1mg/L TPhP completely in 24h via intracellular enzymes through hydrolysis, hydroxylation, methylation, and glutathionylation. However, the use of extracellular enzymes of *Sphingopyxis* sp. GY showcases a limited degradation rate by achieving 33.7% removal of 1mg/L TPhP in 36h. These examples demonstrate that microbial strains can play a significant role in the bioremediation of TPhP.

Kawaguchi et al [116] experimented with a study by isolating bacteria (YS-57) from the leachate of a sea-based waste disposal site for the degradation of aryl-phosphate. The study observed a rapid TPhP removal within 2 days. Additionally, the authors noted that using a pure microbial strain significantly enhances degradation efficiency and reduces the time required for the process. In contrast, Yang and the team reported that bacterial consortium GYY can degrade 92.2% TPhP within 4 hrs under optimal conditions. Further, the team found out that bacterial genera *Pseudathrobacter* and *Sphingopyxis* within the microbial consortium GYY played a pivotal role in degrading TPhP effectively [117]. The bacterial degradation of aryl-OPFRs by *Rhodococcus pyridinivorans* YC-MTN strain [118] and *Rhodococcus-Sphingopyxis* consortium [119] have demonstrated the highest degradation rate of 99.24% TPhP under various environmental conditions.

In addition to bacterial systems, fungal strains have also shown promising potential in TPhP degradation. For instance, Feng et al [120] isolated a novel fungal species, *Aspergillus sydowii* FJH-1. This fungus showed an ability to adapt to various environmental conditions and showcased TPhP degradation of about 90% within 6 days. The degradation of TPhP by *A. sydowii* FJH-1 was linked to a series of biochemical pathways and maintained high biodegradation efficiency across a wide range of pH values between 4-9) at 30°C. In another study, a white rot fungus *Pycnoporus sanguineus* [121] showed 62.84% biodegrading efficiency of 5 mg/L TPhP, when pH and initial glucose concentration were adjusted to 6.0 and 5.0 g/L, respectively. As a result, seven biodegradation products were identified, indicating that TPhP was bio-transformed through oxidative cleavage, hydroxylation, and methylation as depicted in **Fig.3**.

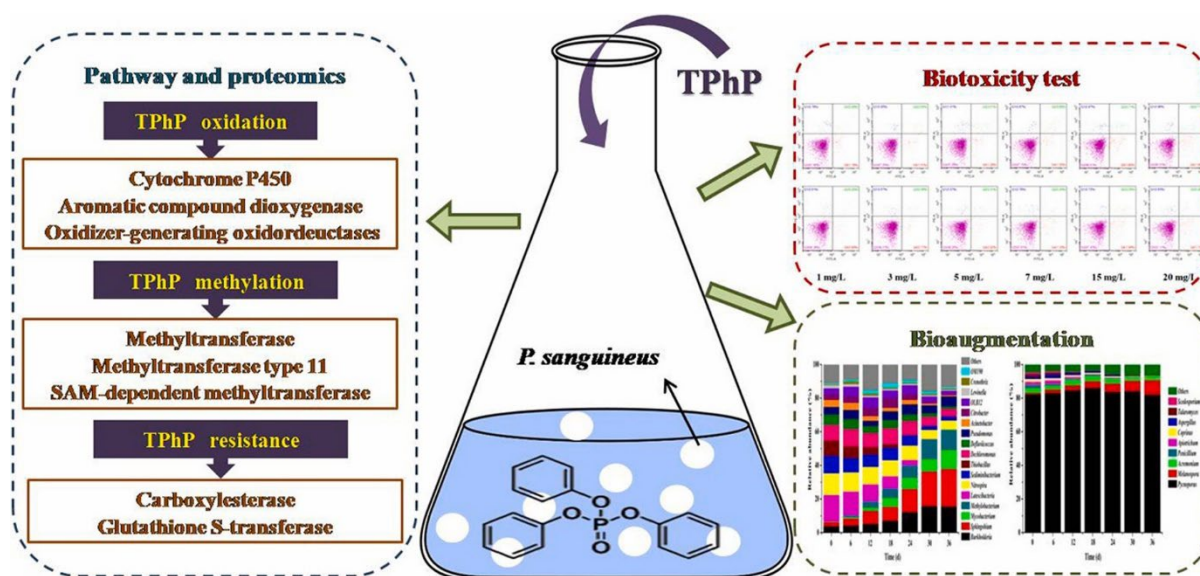


Fig.3. Schematic overview of *P. Sanguineus*-mediated biodegradation of Triphenyl Phosphate (TPhP) (Reproduced with permission from Feng et al., [121])

Lastly, microalgae also play an important role in the degradation of TPhP. A study by Wang et al., [122], reported that microalgal species like *Chlorella vulgaris* (CV) and *Scenedesmus obliquus* have a better ability to hold TPhP in one day and transform it into metabolites. The study deliberately highlighted that *C. vulgaris* acted as a defensive strategy, while *S. obliquus* was irreversibly damaged by reactive oxygen species (ROS) at 10mg/L TPhP.

In addition to bioremediation, Phytoremediation is yet another emerging field that offers cost-effective solutions by using plants and associated soil microbes. It has complex mechanisms and unpredictable influencing factors. Lao et al [123] conducted laboratory-controlled hydroponic/soil culture experiments with water hyacinth to reveal the uptake mechanism and transformation of OPFRs. It was observed that plant roots can absorb pollutants via both active and passive pathways. However, there are only a few studies in this area to remove TPhP from the environment.

5. Remediation in soil:

5.1 Remediation using chemical substances:

Remediation of TPhP using chemical substances in a soil environment has not received much attention due to complex soil composition, reaction oxygen species (ROS) scavenging, and illumination of toxic by-products [124]. However, some research investigations have reported the degradation of TPhP using the advanced oxidation process, catalytic degradation, chemical hydrolysis, and electrochemical degradation. A study by Dong et al [125] demonstrated that ascorbic acid (H_2A) enhanced peroxy disulfate (PDS) activation by promoting the reductive dissolution of iron-containing minerals in soil. This process further increases the content of Fe^{2+} ions and oxygen vacancies on the mineral surfaces, which play a crucial role in the biotransformation of TPhP. The strong two-electron reducing potential of ascorbic acid ($E^\circ = -172$ mV) facilitated the production of ROS, including sulfate radicals ($SO_4^{\cdot-}$) and hydroxyl radicals ($HO^{\cdot}$). These reactive species are highly effective in breaking down TPhP, leading to its degradation and transformation into less harmful by-products. Research on the degradation of the TPhP in soil has focused on evaluating the influence of temperature, soil-to-water ratio, and background inorganic anions on the efficiency of peroxydisulfate (PDS)-based advanced oxidation processes. The study reported various chemical oxidants like - hydrogen peroxide (H_2O_2),

persulfate (PS), peroxymonosulfate (PMS), and their activating agents by ferrous ions (Fe^{2+}) or heat to study the degradation of TPhP in soil. Thus, it is proven that heat-activated PS significantly enhanced TPhP degradation, with a high degradation rate. The reaction temperature also increased the TPhP melting point to (50°C) . The activation energy of the process was calculated to be $115.57\text{ kJ mol}^{-1}$, showcasing the prominence of the heat-assisted oxidation process in remediating TPhP-contaminated soil. This study also investigated the impact of soil-water ratio and background inorganic anions on TPhP degradation. Results showed that increasing the soil-water ratio intensified the inhibitory effect of soil organic matter (SOM) on TPhP degradation, while background inorganic anions like chloride ions (Cl^-) significantly inhibited TPhP degradation in the heat-PS system. However, bicarbonate (HCO_3^-) and dihydrogen phosphate (H_2PO_4^-) ions have minimal effects [126].

On the other hand, Dong et al. [79] conducted a TPhP degradation study in soil and found that the introduction of chelating and reducing agents (CR) facilitated the activation of PDS by soil Fe-minerals. Among the CRs, polyphenols showed an outstanding effect in the degradation of TPhP, resulting in less toxic products like diphenyl phosphate (DPhP) and 4-hydroxyphenyl diphenyl phosphate (OH-TPhP), respectively as shown in Fig.4.

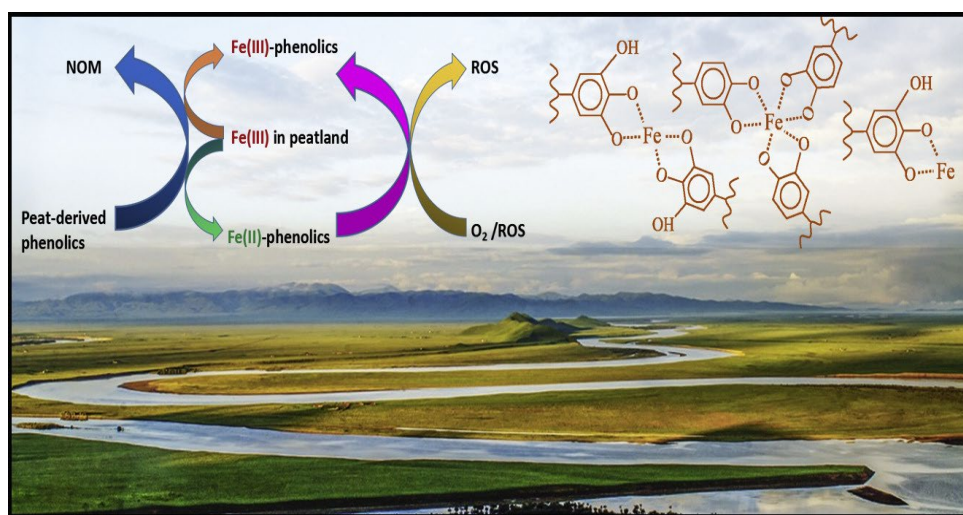


Fig.4. Natural organic matter (NOM)-mediated redox cycling of iron and phenolic compounds in peatland ecosystems (Reproduced with permission from Dong et al [127])

5.2 Remediation using microorganisms and natural substances:

Remediation of TPhP in soil using microorganisms and natural substances such as biochar and plant root exudates has emerged as a sustainable approach in the degradation and removal process (Fig.5). Recent findings indicate that soil contamination in OPFR often results from biosolids-derived sewage sludge, a byproduct of wastewater treatment. Further, these contaminants can leach into groundwater, aggravating environmental risks. As a result, remediation techniques- microbial, phytoremediation, and biochar amendments have been explored for the mitigation of OPFR pollution in soil ecosystems. For instance, a study by Pang et al [128] proved that anaerobic digestion has increased degradation efficiency than aerobic digestion of OPFRs in sewage sludge. The experimental analysis was carried forward under aerobic and anaerobic conditions, with and without pig manure addition. Among the treatments, OPFR degradation under anaerobic digestion with pig manure achieved the highest removal at 28.9%, followed by aerobic composting with pig manure at 19.6%. Further, the study reported that the presence of pig manure in the sewage sludge enhanced the microbial activity, leading to the degradation of OPFR, particularly for TCPP (55.2%), whereas TPhP remained persistent at a lower

removal percentage. Microbe species, including *Pseudomonas*, *Bacillus*, *Alcaligenes*, and *Flavobacterium* played a pivotal role in degrading TPhP.

In addition, a study was conducted using biochar during aerobic composting of sewage sludge to enhance TPhP degradation. Biochar presence primarily influences the microbial structure of compost and increases the redox ability of oxygen-containing functional groups, further supporting OPFR degradation [129]. Similarly, Du et al., [69] demonstrated a sorption study on aromatic OPFRs using thermally (pyrochar) and hydrothermally (hydrochar) produced biochar. Further, the study illustrated that pyrochar exhibits higher sorption efficiency, with PRS600 showing 524.7 mg/kg for TPhP, and 60.4 mg/kg for TPPO outperforming PRS450 and PRS300. Significantly, hydrochar showed less sorption capacity of 2.7 mg/kg for Triphenylphosphine oxide (TPPO), but the exact efficiency of TPhP was not explicitly stated. The enhanced sorption efficiency was attributed to the electrostatic attraction between the protonated P = O in TPhP and the negatively charged biochar surface.

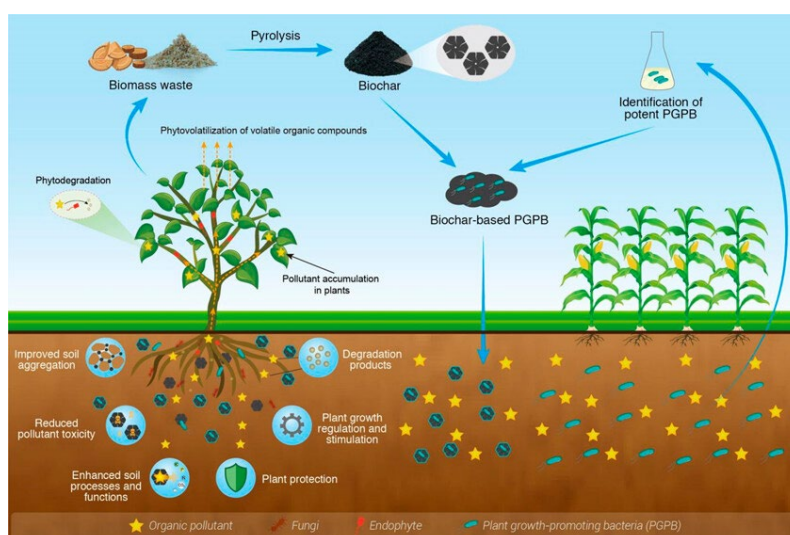


Fig.5. Integrated role of biochar and plant growth-promoting bacteria (PGPB) during phytoremediation of organic pollutants. (Reproduced with permission from Xiang et al [131])

Apart from microbial remediation, phytoremediation acts as an attractive strategy for the degradation of TPhP from soil. As an illustration, Deng and the team conducted a study using ryegrass (*Lolium perenne*), which produces oxalic acid in its root exudates, facilitating the dissipation of TPhP from the soil. The experimental analysis reported that oxalic acid in ryegrass enhances the degradation of TPhP by stimulating microbial and enzyme (phosphatase, dehydrogenase, and catalase) activities in soil. Additionally, the study identified the microbial genera behind the TPhP degradation, such as *Sphingomonas*, *Pseudomonas*, *Flavisolibacter*, *Pontibacter*, *Methylophilus*, and *Massilia*. The dissipation rate of TPhP was found to increase over time, with oxalic acid further accelerating the process. However, it is also important to note that the degradation of TPhP leads to the formation of highly toxic DPhP.

Remediation of TPhP in sediments is even more scarce, but it is of utmost importance as TPhP found in sediments could also contaminate groundwater. Wang et al [130] studied the sorption and desorption behavior of TPhP in aquatic sediments and reported a sorption capacity of 0.433 $\mu\text{mol/g}$ for TPhP and

0.414 $\mu\text{mol/g}$ for DPhP in natural sediments. Sediment with 5% humic acid exhibited higher and sediment with SOM (Soil Organic Matter) exhibited lower sorption capacity than natural sediment. Kawaguchi et al [79] investigated the degradation behavior of OPFRs in leachate from a sea-based solid waste disposal site. The study concluded that TPhP concentration decreased rapidly under aerobic conditions. Nevertheless, studies on the remediation of TPhP in the soil environment remain highly limited, highlighting the need for further research on the effective removal of TPhP using natural substances.

6. Analytical techniques for the detection of TPhP and other OPFR across different methods:

As TPhP and other OPFR continue to be detected in various environmental compartments—including soil, water, and biota—their persistence and toxicity necessitate a reliable analytical monitoring. In this context, accurate detection plays a crucial role in assessing the removal as well as the presence of TPhP from various matrices such as soil and water. While various analytical techniques are used to quantify the presence of TPhP but the precise detection remains limited. TPhP detecting techniques are broadly distinguished based on spectroscopy and chromatography. Detection using the chromatographic method involves Gas Chromatography-Mass Spectrometry (GC-MS) and High-Performance Liquid Chromatography (HPLC). GC-MS methods are widely used for detecting volatile and semi-volatile organic compounds like TPhP and other OPFR compounds based on their sensitivity and specificity. The reason for analysing the TPhP in GC-MS is predominantly due to its ability to differentiate similar compounds through the mass-to-charge (m/z) ratio of ionized fragments.

For instance, Chen and his team [146] developed a rapid and environmentally friendly method using GC-MS to detect TPhP and ten other OPFRs in indoor air, house dust, and skin wipe samples. Their study resulted in an optimized extraction method to minimize solvent use and maximize sensitivity in detection. They demonstrated a high accuracy and precision in identifying TPhP in indoor air based on its m/z ratio and retention time, respectively. At last, the study proved that GC-MS acts as a reliable tool for monitoring flame retardant contamination (TPhP) in an indoor environment via an optimized extraction method. Likewise, Wang et al. [147] introduced a GC-MS method for detecting OPFR in ambient water samples using a coupled magnetic solid phase extraction (SPE) with multi-walled carbon nanotube (MWCNT)-coated iron oxide (Fe_3O_4) as the adsorbent. This method exhibited an OPFR recovery of 72.5%- 89.1% in the spiked samples with low, medium, and high-concentration analytes. Furthermore, the LOD and LOQ of the GC-MS method were reported to possess 0.038–1 $\mu\text{g/L}$ and 0.10–3.59 $\mu\text{g/L}$.

HPLC is another chromatographic technique used to analyse the presence of TPhP in both aqueous and biological samples. These techniques are ideal due to their high sensitivity, accuracy, and reproducibility at trace levels. Several studies have reported the effectiveness of TPhP. Notably, a study by Kowalski and Mazur [148] confirmed the HPLC method's reliability via high precision and low detection limit through an optimized Solid-Phase Extraction (SPE) method for quantifying TPhP in water samples. HPLC coupled with UV or MS detection was used to examine the presence of TPhP in wastewater, consumer products, and biological fluids. For instance, the U.S. Consumer Product Safety Commission [149] investigated the presence of flame-retardant chemicals like TPhP in consumer products like foam and fabrics. The study employed sample extraction followed by HPLC analysis, which effectively reported the reliable quantification of OPFR, particularly TPhP. The result indicated a measurable concentration of TPhP in various consumer products, highlighting potential exposure risks. This study demonstrated HPLC as an effective method for the detection and quantification of TPhP.

Apart from the chromatographic technique, spectroscopic analysis possesses the ability to detect and characterize TPhP presence in various matrices using FTIR and UV-Vis spectroscopy. These techniques specifically provide structural and functional group information on the identification of TPhP. Trivedi et al., [150] in a study, investigated the impact of biofield treatment on the physicochemical and spectroscopic properties of TPhP. To analyze the potential changes in TPhP structure, their study employed FTIR and UV-vis spectroscopy to confirm the stability of TPhP before and after the treatment process. Using FTIR spectra, both control and treated TPhP samples were analyzed with the frequency range of 500-4000 cm^{-1} . The analysis result reported no change in the wavenumbers associated with the functional groups such as C-H, C=C, P=O, and P-O bonds. At last, it was concluded that the TPhP in the treated sample remained unchanged. Similarly, UV-vis spectroscopy displayed a consistent absorbance peak at 204-205 nm, 254-256 nm, and 262-263 nm. As a result, it was the biofield treatment didn't show any impact on the electronic structure of TPhP, reinforcing the spectroscopic method as a reliable method for structural assessment.

7. Challenges and Strategic Interventions in the Remediation of TPhP and Related OPFRs

Key challenges in the mitigation of TPhP and related OPFR from the environment lie in their inherent chemical persistence, low biodegradability, and pronounced tendency to accumulate in environmental compartments such as sediments and biota. Moreover, these characteristics not only hinder natural attenuation but also pose a long-term ecological exposure via transformation of TPhP and other OPFRs as a by-product. Significantly, the transformed byproducts are more toxic than their parent compounds, thereby creating complexity to remediation efforts, as conventional treatment methods may fail to achieve complete degradation or effective removal of these substances. Consequently, this poses a risk to aquatic and terrestrial ecosystems by disrupting ecological balance and human health.

Addressing these challenges requires a multi-layered strategy that integrates technological innovation with regulatory and preventive measures. Typically, advanced treatment technologies such as adsorption using biochar, activated carbon, and functionalized nanomaterials have shown a promising potential in the degradation of TPhP and other OPFR effectively. In addition, AOP's including photocatalysis, ozonation, and Fenton-like reactions, offer efficient pathways for the degradation of both parent compounds and their toxic by-products. Furthermore, bioremediation approaches, utilizing specialized microbial strains or enzymatic systems, have demonstrated the capability to remove TPhP and other OPFR sustainably. This method offers an eco-friendly alternative and is widely suitable for in situ applications in contaminated soils and aquatic systems. Moreover, this method often requires a longer treatment process and controlled environmental conditions for effective removal. However, optimizing these processes for real-world application remains a challenge due to their operational complexity, energy demand, cost constraints, and potential formation of secondary pollutants.

Continued research is needed to enhance process efficiency, develop hybrid systems, and tailor solutions to site-specific conditions. In particular, further investigation into biological treatment methods is needed due to their eco-friendly potential and applicability in real-world scenarios. In parallel, strict regulations must be enforced, along with the promotion of safer chemical alternatives to reduce environmental input of OPFR. Some of the regulatory frameworks involve REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) in the EU, and the adoption of life-cycle assessment (LCA) and extended producer responsibility (EPR) principles to reduce environmental loading at the source [151]. In addition, reliable detection and monitoring also remain a major hurdle due to the structural diversity and trace concentration of OPFR and their metabolites. Moreover, advancement in the analytical tools needs to be improved for accurate environmental assessment of

OPFR and its risk evaluation. Risk-based prioritization approaches should also be applied to identify the most hazardous OPFRs, enabling targeted remediation strategies.

On the other hand, public awareness and stakeholder engagement are critical components of any long-term mitigation strategy. Educating consumers about the environmental impact of OPFR-containing products, promoting product labelling, and encouraging the use of safer alternatives can significantly reduce OPFR input into ecosystems. Ultimately, the successful mitigation of TPhP and related OPFR contamination requires an interdisciplinary approach by combining scientific innovation, policy enforcement, and industrial responsibility to ensure protection over environmental and public health.

Conclusion

This review predominantly highlights effective strategies for remediating hazardous TPhP and other OPFR contamination in water, soil, and other miscellaneous matrices. Various remediation approaches like chemical, biological, and natural-based methods have demonstrated a significant potential in mitigating pollution caused by TPhP in water and soil systems. Among chemical techniques, advanced oxidation and photocatalysis methods have shown rapid removal and degradation of TPhP. However, these methods are limited by generating harmful by-products, affecting environmental safety, and often involve higher operational costs. Meanwhile, biological and natural-based approaches involving microbes, biochar, and so on, have emerged as an effective alternative, by facilitating the breakdown of TPhP into less toxic compounds. Nonetheless, both biological and nature-based methods have limitations, as they require selective environmental conditions—such as optimal pH, temperature, and nutrient availability—that are critical for microbial activity and the adsorption efficiency of TPhP and other OPFR. By evaluating all strategies within a unified framework based on key criteria such as removal efficiency, remediation time, sustainability, scalability, potential risks, and secondary impacts. The review thus provides a comprehensive perspective to support the selection of context-appropriate remediation approaches for both water and soil systems.

Despite the promising outcomes reported in existing literature, significant challenges in the removal and degradation of TPhP prevail in the form of incomplete degradation, environmental persistence, and the formation of toxic by-products in the TPhP remediation process. Based on the observation from the literature, it is understood that future research needs to focus on developing an integrated approach combining chemical, biological, and natural-based methods to achieve an enhanced remediation efficiency of TPhP and other OPFR without notable challenges. Additionally, this review paper identifies a significant knowledge gap in understanding the degradation pathway and environmental behaviour of TPhP, underscoring the need for developing effective and sustainable remediation strategies. Further research focusing on TPhP contamination via soil needs to be addressed largely, as the studies on TPhP remain scarce compared to studies that were focused on water.

In summary, continuous research and innovation are essential to witness robust and eco-friendly strategies for the remediation of TPhP and similar emerging pollutants, considering long-term environmental health and safety via air, water, and soil.

CRedit authorship contribution statement

Vasanthiya Tej A: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Pranika M:** Methodology, Investigation. **Adhithya S:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **K. Nithya:** Writing – review & editing, Validation, Supervision, Data curation. **Asha Sathish:** Writing – review & editing, Validation, Supervision, Data curation. **V. Kumar:** Reviewing and revising.

Funding

This study was supported through the AMRITA Seed Grant (Proposal ID: ASG2022146).

References

- [1] R. A. Mensah *et al.*, “A review of sustainable and environment-friendly flame retardants used in plastics,” *Polym. Test.*, vol. 108, p. 107511, 2022, <https://doi.org/10.1016/j.polymertesting.2022.107511>.
- [2] J. Shen, J. Liang, X. Lin, H. Lin, J. Yu, and S. Wang, “The Flame-Retardant Mechanisms and Preparation of Polymer Composites and Their Potential Application in Construction Engineering,” *Polymers (Basel)*, vol. 14, no. 1, Dec. 2021, doi: 10.3390/polym14010082.
- [3] X. Li, J. Ma, D. Fang, T. Shi, and Y. Gong, “Organophosphate Flame Retardants in Soils of Zhejiang Province, China: Levels, Distribution, Sources, and Exposure Risks,” *Arch. Environ. Contam. Toxicol.*, vol. 78, no. 2, pp. 206–215, Feb. 2020, doi: 10.1007/s00244-019-00675-0.
- [4] L. Pang, Y. Yuan, H. He, K. Liang, H. Zhang, and J. Zhao, “Occurrence, distribution, and potential affecting factors of organophosphate flame retardants in sewage sludge of wastewater treatment plants in Henan Province, Central China,” *Chemosphere*, vol. 152, pp. 245–251, 2016, <https://doi.org/10.1016/j.chemosphere.2016.02.104>.
- [5] J. Zhou, C. Liang, J. Li, J. Gu, A. Salamova, and L. Liu, “Consumer products are important reservoirs and sources of organophosphate tri-esters and di-esters: Characteristics, mass inventory, and implication for waste management,” *J. Environ. Sci.*, vol. 151, pp. 550–559, 2025, <https://doi.org/10.1016/j.jes.2024.04.008>.
- [6] Y. Lan, X. Gao, H. Xu, and M. Li, “20 years of polybrominated diphenyl ethers on toxicity assessments,” *Water Res.*, vol. 249, p. 121007, 2024, <https://doi.org/10.1016/j.watres.2023.121007>.
- [7] Q. Yu, H.-B. Xie, and J. Chen, “Atmospheric chemical reactions of alternatives of polybrominated diphenyl ethers initiated by OH: A case study on triphenyl phosphate,” *Sci. Total Environ.*, vol. 571, pp. 1105–1114, 2016, <https://doi.org/10.1016/j.scitotenv.2016.07.105>.
- [8] M. Hou, Y. Shi, G. Na, and Y. Cai, “A review of organophosphate esters in indoor dust, air, hand wipes and silicone wristbands: Implications for human exposure,” *Environ. Int.*, vol. 146, p. 106261, 2021, <https://doi.org/10.1016/j.envint.2020.106261>.
- [9] Y. X. Tian, H. Y. Chen, J. Ma, Q. Y. Liu, Y. J. Qu, and W. H. Zhao, “A critical review on sources and environmental behavior of organophosphorus flame retardants in the soil: Current knowledge and future perspectives” *J Hazard Mater.* 2023 Jun 15;452:131161. doi: 10.1016/j.jhazmat.2023.131161..
- [10] T. J. McGrath, A. S. Ball, and B. O. Clarke, “Critical review of soil contamination by polybrominated diphenyl ethers (PBDEs) and novel brominated flame retardants (NBFRs); concentrations, sources and congener profiles” *Environ Pollut.* 2017 Nov;230:741-757. doi: 10.1016/j.envpol.2017.07.009.
- [11] I. Pantelaki and D. Voutsas, “Organophosphate flame retardants (OPFRs): A review on analytical methods and occurrence in wastewater and aquatic environment,” *Sci. Total Environ.*, vol. 649, pp. 247–263, 2019, <https://doi.org/10.1016/j.scitotenv.2018.08.286>.
- [12] W. Luo, Y. Liu, X. Yang, M. Aamir, X. Bai, and W. Liu, “Prenatal exposure to emerging and

- traditional organophosphate flame retardants: Regional comparison, transplacental transfer, and birth outcomes,” *Environ. Pollut.*, vol. 336, p. 122463, 2023, <https://doi.org/10.1016/j.envpol.2023.122463>.
- [13] X. Ge, S. Ma, X. Zhang, Y. Yang, G. Li, and Y. Yu, “Halogenated and organophosphorous flame retardants in surface soils from an e-waste dismantling park and its surrounding area: Distributions, sources, and human health risks,” *Environ. Int.*, vol. 139, p. 105741, 2020, <https://doi.org/10.1016/j.envint.2020.105741>.
 - [14] N. Marlina *et al.*, “Organophosphate esters in water and air: A minireview of their sources, occurrence, and air–water exchange,” *Chemosphere*, vol. 356, p. 141874, 2024, doi: <https://doi.org/10.1016/j.chemosphere.2024.141874>.
 - [15] J. Li *et al.*, “A review on organophosphate Ester (OPE) flame retardants and plasticizers in foodstuffs: Levels, distribution, human dietary exposure, and future directions,” *Environ. Int.*, vol. 127, pp. 35–51, 2019, <https://doi.org/10.1016/j.envint.2019.03.009>.
 - [16] L. Zhao *et al.*, “Organophosphate esters (OPEs) in Chinese foodstuffs: Dietary intake estimation via a market basket method, and suspect screening using high-resolution mass spectrometry,” *Environ. Int.*, vol. 128, pp. 343–352, 2019, <https://doi.org/10.1016/j.envint.2019.04.055>.
 - [17] Y. Choi, J. Jeon, and S. D. Kim, “Identification of biotransformation products of organophosphate ester from various aquatic species by suspect and non-target screening approach,” *Water Res.*, vol. 200, p. 117201, 2021, <https://doi.org/10.1016/j.watres.2021.117201>.
 - [18] I. van der Veen and J. de Boer, “Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity and analysis,” *Chemosphere*, vol. 88, no. 10, pp. 1119–1153, 2012, <https://doi.org/10.1016/j.chemosphere.2012.03.067>.
 - [19] K. Xiao *et al.*, “Occurrence, distribution and risk assessment of organophosphate ester flame retardants and plasticizers in surface seawater of the West Pacific,” *Mar. Pollut. Bull.*, vol. 170, p. 112691, 2021, <https://doi.org/10.1016/j.marpolbul.2021.112691>.
 - [20] L. Zhou *et al.*, “Besides traditional organophosphate esters: The ecological risks of emerging organophosphate esters in the Yangtze River basin cannot be ignored,” *Environ. Pollut.*, vol. 367, p. 125585, 2025, <https://doi.org/10.1016/j.envpol.2024.125585>.
 - [21] C. Yao, H. Yang, and Y. Li, “A review on organophosphate flame retardants in the environment: Occurrence, accumulation, metabolism and toxicity,” *Sci. Total Environ.*, vol. 795, p. 148837, 2021, <https://doi.org/10.1016/j.scitotenv.2021.148837>.
 - [22] Z. Yan *et al.*, “Unbalanced Pollution and Ecological Risk of Organophosphate Esters in Chinese Surface Water and Land Use Under Multiple Driving Factors,” *Rev. Environ. Contam. Toxicol.*, vol. 261, no. 1, p. 18, 2023, doi: 10.1007/s44169-023-00041-1.
 - [23] W. Jun, H. Xi, L. Zhang, and H. Liu, “Organophosphorus flame retardants in the Qiantang River of China : occurrence , source and ecological risk assessment,” *Environ. Geochem. Health*, vol. 46, no. 10, pp. 1–16, 2024, doi: 10.1007/s10653-024-02172-3.
 - [24] L. Zhang, C. Yan, J. Ma, R. Hou, and L. Lu, “Organophosphate esters in edible marine fish: Tissue-specific distribution, species-specific bioaccumulation, and human exposure,” *Environ. Pollut.*, vol. 345, p. 123560, 2024, <https://doi.org/10.1016/j.envpol.2024.123560>.
 - [25] Z. Du, Y. Zhang, G. Wang, J. Peng, Z. Wang, and S. Gao, “TPhP exposure disturbs carbohydrate metabolism, lipid metabolism, and the DNA damage repair system in zebrafish

- liver.,” *Sci. Rep.*, vol. 6, p. 21827, Feb. 2016, doi: 10.1038/srep21827.
- [26] S. Adhithya, K. Nithya, A. Sathish, and V. Kumar, “Uncovering the feasibility of using live *Chlorella* microbiomes in domestic and industrial wastewater treatment: Insights into monoculture and synergistic mixed co-cultured system,” *J. Ind. Eng. Chem.*, 2025, <https://doi.org/10.1016/j.jiec.2025.02.006>.
 - [27] J. Hong *et al.*, “Triphenyl phosphate disturbs placental tryptophan metabolism and induces neurobehavior abnormal in male offspring,” *Ecotoxicol. Environ. Saf.*, vol. 243, p. 113978, 2022, <https://doi.org/10.1016/j.ecoenv.2022.113978>.
 - [28] E. M. A *et al.*, “Nail polish as a source of exposure to triphenyl phosphate”.
 - [29] B. Sonawane, D. Ph, A. M. Kadry, and D. Ph, “Electronic Waste : Human Health and Environmental Risk,” pp. 1–18, 2024, doi: 10.1002/0471125474.tox163.
 - [30] J. O. Osuoha, B. O. Anyanwu, and C. Ejileugha, “Pharmaceuticals and personal care products as emerging contaminants: Need for combined treatment strategy,” *J. Hazard. Mater. Adv.*, vol. 9, p. 100206, 2023, <https://doi.org/10.1016/j.hazadv.2022.100206>.
 - [31] P. Amoatey and M. S. Baawain, “Effects of pollution on freshwater aquatic organisms,” *Water Environ. Res.*, vol. 91, no. 10, pp. 1272–1287, Oct. 2019, <https://doi.org/10.1002/wer.1221>.
 - [32] T. Wang *et al.*, “Occurrence and potential risks of organophosphate esters in agricultural soils: A case study of Fuzhou City, Southeast China,” *J. Environ. Sci.*, vol. 150, pp. 571–581, 2025, <https://doi.org/10.1016/j.jes.2024.03.005>.
 - [33] H. M. Stapleton *et al.*, “Detection of Organophosphate Flame Retardants in Furniture Foam and U.S. House Dust,” *Environ. Sci. Technol.*, vol. 43, no. 19, pp. 7490–7495, Oct. 2009, doi: 10.1021/es9014019.
 - [34] L. Wang, X. Huang, A. K. C. Laserna, and S. F. Y. Li, “Untargeted metabolomics reveals transformation pathways and metabolic response of the earthworm *Perionyx excavatus* after exposure to triphenyl phosphate,” *Sci. Rep.*, vol. 8, no. 1, p. 16440, 2018, doi: 10.1038/s41598-018-34814-9.
 - [35] L. Philippot, C. Chenu, A. Kappler, M. C. Rillig, and N. Fierer, “The interplay between microbial communities and soil properties,” *Nat. Rev. Microbiol.*, vol. 22, no. 4, pp. 226–239, 2024, doi: 10.1038/s41579-023-00980-5.
 - [36] M. Naz *et al.*, “The soil pH and heavy metals revealed their impact on soil microbial community,” *J. Environ. Manage.*, vol. 321, p. 115770, 2022, <https://doi.org/10.1016/j.jenvman.2022.115770>.
 - [37] M. O. Adomako, S. Roiloa, and F.-H. Yu, “Potential Roles of Soil Microorganisms in Regulating the Effect of Soil Nutrient Heterogeneity on Plant Performance.,” *Microorganisms*, vol. 10, no. 12, Dec. 2022, doi: 10.3390/microorganisms10122399.
 - [38] L. Wang *et al.*, “Strategies to improve soil health by optimizing the plant–soil–microbe–anthropogenic activity nexus,” *Agric. Ecosyst. Environ.*, vol. 359, p. 108750, 2024, <https://doi.org/10.1016/j.agee.2023.108750>.
 - [39] C. Ye *et al.*, “Triphenyl phosphate exposure impairs colorectal health by altering host immunity and colorectal microbiota,” *Chemosphere*, vol. 349, p. 140905, 2024, <https://doi.org/10.1016/j.chemosphere.2023.140905>.
 - [40] Z. Hong *et al.*, “Comprehensive analysis of triphenyl phosphate: An environmental explanation of colorectal cancer progression,” *Ecotoxicol. Environ. Saf.*, vol. 241, p. 113778,

- 2022, <https://doi.org/10.1016/j.ecoenv.2022.113778>.
- [41] D. Yadav *et al.*, “Environmental and health impacts of contaminants of emerging concerns: Recent treatment challenges and approaches,” *Chemosphere*, vol. 272, p. 129492, 2021, <https://doi.org/10.1016/j.chemosphere.2020.129492>.
 - [42] S. Vardoulakis, K. Dear, and P. Wilkinson, “Challenges and Opportunities for Urban Environmental Health and Sustainability: the HEALTHY-POLIS initiative,” *Environ. Heal.*, vol. 15, no. 1, p. S30, 2016, doi: 10.1186/s12940-016-0096-1.
 - [43] Y.-L. Luo *et al.*, “Leveraging the water-environment-health nexus to characterize sustainable water purification solutions,” *Nat. Commun.*, vol. 16, no. 1, p. 1269, 2025, doi: 10.1038/s41467-025-56656-6.
 - [44] C. F. Estill *et al.*, “Assessment of triphenyl phosphate (TPhP) exposure to nail salon workers by air, hand wipe, and urine analysis,” *Int. J. Hyg. Environ. Health*, vol. 231, p. 113630, Jan. 2021, doi: 10.1016/j.ijheh.2020.113630.
 - [45] L. Germain and L. M. Winn, “The flame retardant triphenyl phosphate alters the epigenome of embryonic cells in an aquatic in vitro model,” *J. Appl. Toxicol.*, vol. 44, no. 7, pp. 965–977, Jul. 2024, <https://doi.org/10.1002/jat.4589>.
 - [46] “Registration Dossier - ECHA.” [Online]. Available: <https://echa.europa.eu/registration-dossier/-/registered-dossier/15972/6/1>
 - [47] W. Wan, S. Zhang, H. Huang, and T. Wu, “Occurrence and distribution of organophosphorus esters in soils and wheat plants in a plastic waste treatment area in China,” *Environ. Pollut.*, vol. 214, pp. 349–353, 2016, <https://doi.org/10.1016/j.envpol.2016.04.038>.
 - [48] Y. Choi, J. Jeon, Y. Choi, and S. D. Kim, “Characterizing biotransformation products and pathways of the flame retardant triphenyl phosphate in *Daphnia magna* using non-target screening,” *Sci. Total Environ.*, vol. 708, p. 135106, 2020, <https://doi.org/10.1016/j.scitotenv.2019.135106>.
 - [49] N. Van den Eede, A. C. Dirtu, H. Neels, and A. Covaci, “Analytical developments and preliminary assessment of human exposure to organophosphate flame retardants from indoor dust,” *Environ. Int.*, vol. 37, no. 2, pp. 454–461, 2011, <https://doi.org/10.1016/j.envint.2010.11.010>.
 - [50] U.-J. Kim, Y. Wang, W. Li, and K. Kannan, “Occurrence of and human exposure to organophosphate flame retardants/plasticizers in indoor air and dust from various microenvironments in the United States,” *Environ. Int.*, vol. 125, pp. 342–349, 2019, <https://doi.org/10.1016/j.envint.2019.01.065>.
 - [51] C. F. Estill, J. Slone, A. Mayer, I.-C. Chen, and M. J. La Guardia, “Worker exposure to flame retardants in manufacturing, construction and service industries,” *Environ. Int.*, vol. 135, p. 105349, 2020, <https://doi.org/10.1016/j.envint.2019.105349>.
 - [52] E. Mendelsohn *et al.*, “Nail polish as a source of exposure to triphenyl phosphate,” *Environ. Int.*, vol. 86, pp. 45–51, 2016, <https://doi.org/10.1016/j.envint.2015.10.005>.
 - [53] K. Hoffman, S. Garantziotis, L. S. Birnbaum, and H. M. Stapleton, “Monitoring Indoor Exposure to Organophosphate Flame Retardants: Hand Wipes and House Dust,” *Environ. Health Perspect.*, vol. 123, pp. 160–165, 2014, [Online]. Available: <https://api.semanticscholar.org/CorpusID:5559419>
 - [54] F. Wong, C. A. de Wit, and S. R. Newton, “Concentrations and variability of organophosphate esters, halogenated flame retardants, and polybrominated diphenyl ethers in indoor and

- outdoor air in Stockholm, Sweden,” *Environ. Pollut.*, vol. 240, pp. 514–522, 2018, <https://doi.org/10.1016/j.envpol.2018.04.086>.
- [55] X. Fan, C. Kubwabo, P. E. Rasmussen, and F. Wu, “Simultaneous determination of thirteen organophosphate esters in settled indoor house dust and a comparison between two sampling techniques” *Sci Total Environ.* 2014 Sep 1;491-492:80-6. doi: 10.1016/j.scitotenv.2013.12.127..
 - [56] M. A.-E. Abdallah and A. Covaci, “Organophosphate flame retardants in indoor dust from Egypt: implications for human exposure.,” *Environ. Sci. Technol.*, vol. 48, no. 9, pp. 4782–4789, May 2014, doi: 10.1021/es501078s.
 - [57] N. Ali *et al.*, “Occurrence of alternative flame retardants in indoor dust from New Zealand: Indoor sources and human exposure assessment,” *Chemosphere*, vol. 88, no. 11, pp. 1276–1282, 2012, <https://doi.org/10.1016/j.chemosphere.2012.03.100>.
 - [58] S. Lee, W. Jeong, K. Kannan, and H.-B. Moon, “Occurrence and exposure assessment of organophosphate flame retardants (OPFRs) through the consumption of drinking water in Korea,” *Water Res.*, vol. 103, pp. 182–188, 2016, <https://doi.org/10.1016/j.watres.2016.07.034>.
 - [59] P. Kurt-Karakus, H. Alegria, A. Birgul, E. Gungormus, and L. Jantunen, “Organophosphate ester (OPEs) flame retardants and plasticizers in air and soil from a highly industrialized city in Turkey,” *Sci. Total Environ.*, vol. 625, pp. 555–565, 2018, <https://doi.org/10.1016/j.scitotenv.2017.12.307>.
 - [60] M. Sahoo, “Impact of industrialization , urbanization , and financial development on energy consumption : Empirical evidence from India,” no. August 2019, 2020, doi: 10.1002/pa.2089.
 - [61] R. Lu *et al.*, “Organophosphate flame retardants and plastics in soil from an abandoned e - waste recycling site : significant ecological risks derived from plastic debris,” *Environ. Sci. Pollut. Res.*, pp. 58933–58943, 2023, doi: 10.1007/s11356-023-26625-x.
 - [62] S. Umamaheswari, P. Karthika, K. Suvenitha, K. Kadirvelu, and M. Ramesh, “Dose-Dependent Molecular Responses of *Labeo rohita* to Triphenyl Phosphate,” 2021, doi: 10.1021/acs.chemrestox.1c00281.
 - [63] C.-T. He *et al.*, “Occurrence of organophosphorus flame retardants in indoor dust in multiple microenvironments of southern China and implications for human exposure,” *Chemosphere*, vol. 133, pp. 47–52, 2015, <https://doi.org/10.1016/j.chemosphere.2015.03.043>.
 - [64] W. Li, Y. Shi, L. Gao, C. Wu, J. Liu, and Y. Cai, “Occurrence, distribution and risk of organophosphate esters in urban road dust in Beijing, China,” *Environ. Pollut.*, vol. 241, pp. 566–575, 2018, <https://doi.org/10.1016/j.envpol.2018.05.092>.
 - [65] K. Cui, J. Wen, F. Zeng, S. Li, X. Zhou, and Z. Zeng, “Occurrence and distribution of organophosphate esters in urban soils of the subtropical city, Guangzhou, China,” *Chemosphere*, vol. 175, pp. 514–520, 2017, <https://doi.org/10.1016/j.chemosphere.2017.02.070>.
 - [66] Y. Wang *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.*, vol. 625, pp. 1056–1064, 2018, <https://doi.org/10.1016/j.scitotenv.2018.01.013>.
 - [67] U. E. Bollmann, A. Möller, Z. Xie, R. Ebinghaus, and J. W. Einax, “Occurrence and fate of organophosphorus flame retardants and plasticizers in coastal and marine surface waters,” *Water Res.*, vol. 46, no. 2, pp. 531–538, 2012, <https://doi.org/10.1016/j.watres.2011.11.028>.
 - [68] M. M. Mortula, S. Atabay, K. P. Fattah, and A. Madbulay, “Leachability of microplastic from

- different plastic materials” *J Environ Manage.* 2021 Sep 15;294:112995. doi: 10.1016/j.jenvman.2021.112995. .
- [69] Du, Z., Huang, C., Meng, J. *et al.* Sorption of aromatic organophosphate flame retardants on thermally and hydrothermally produced biochars. *Front. Environ. Sci. Eng.* 14, 43 (2020). <https://doi.org/10.1007/s11783-020-1220-6>
 - [70] Y. Ji *et al.*, “Occurrence of organophosphate flame retardants in farmland soils from Northern China: Primary source analysis and risk assessment,” *Environ. Pollut.*, vol. 247, pp. 832–838, 2019, <https://doi.org/10.1016/j.envpol.2019.01.036>.
 - [71] Zhang, Q., Mei, W., Jiang, L. *et al.* Environmental fate and effects of organophosphate flame retardants in the soil-plant system. *Soil Ecol. Lett.* 3, 178–188 (2021). <https://doi.org/10.1007/s42832-021-0084-4>
 - [72] Y. Liu *et al.*, “Occurrence and partitioning behavior of organophosphate esters in surface water and sediment of a shallow Chinese freshwater lake (Taihu Lake): Implication for eco-toxicity risk,” *Chemosphere*, vol. 202, pp. 255–263, 2018, <https://doi.org/10.1016/j.chemosphere.2018.03.108>.
 - [73] J. Ding, X. Shen, W. Liu, A. Covaci, and F. Yang, “Occurrence and risk assessment of organophosphate esters in drinking water from Eastern China,” *Sci. Total Environ.*, vol. 538, pp. 959–965, 2015, <https://doi.org/10.1016/j.scitotenv.2015.08.101>.
 - [74] Y. Wang *et al.*, “Toxic effect of triphenyl phosphate (TPHP) on *Cyprinus carpio* and the intestinal microbial community response,” *Chemosphere*, vol. 299, p. 134463, 2022, <https://doi.org/10.1016/j.chemosphere.2022.134463>.
 - [75] G.-H. Ding, Z.-Y. Wang, J.-Y. Chen, Q.-Q. Wu, and Y.-N. Zhou, “Comprehensive assessment of the ecological risk of exposure to triphenyl phosphate in a bioindicator tadpole” *Chemosphere*, 308. 136242 doi:10.1016/j.chemosphere.2022.136242.
 - [76] Y. Wang, P. Kannan, R. U. Halden, and K. Kannan, “A nationwide survey of 31 organophosphate esters in sewage sludge from the United States,” *Sci. Total Environ.*, vol. 655, pp. 446–453, 2019, <https://doi.org/10.1016/j.scitotenv.2018.11.224>.
 - [77] Y. Wang *et al.*, “A nationwide survey of 19 organophosphate esters in soils from China: Spatial distribution and hazard assessment,” *Sci. Total Environ.*, vol. 671, pp. 528–535, 2019, <https://doi.org/10.1016/j.scitotenv.2019.03.335>.
 - [78] Y. Li *et al.*, “Occurrence and ecological implications of organophosphate triesters and diester degradation products in wastewater, river water, and tap water,” *Environ. Pollut.*, vol. 259, p. 113810, 2020, <https://doi.org/10.1016/j.envpol.2019.113810>.
 - [79] Y. K. N. Fukunaga, “Degradation of organophosphoric esters in leachate from a sea-based solid waste disposal site” *Chemosphere*. 2002 Jul;48(2):219-25. doi: 10.1016/s0045-6535(02)00051-6. PMID: 12117057.
 - [80] Schwarzbauer J, Heim S, Brinker S, Littke R. Occurrence and alteration of organic contaminants in seepage and leakage water from a waste deposit landfill. *Water Res.* 2002 May;36(9):2275-87. doi: 10.1016/s0043-1354(01)00452-3.
 - [81] Y. Huang *et al.*, “A broad range of organophosphate tri- and di-esters in house dust from Adelaide, South Australia: Concentrations, compositions, and human exposure risks,” *Environ. Int.*, vol. 142, p. 105872, 2020, <https://doi.org/10.1016/j.envint.2020.105872>.
 - [82] M. U. Khan, J. Li, G. Zhang, and R. N. Malik, “First insight into the levels and distribution of flame retardants in potable water in Pakistan: An underestimated problem with an associated

- health risk diagnosis,” *Sci. Total Environ.*, vol. 565, pp. 346–359, 2016, <https://doi.org/10.1016/j.scitotenv.2016.04.173>.
- [83] D. Zhang *et al.*, “The influence of an upgrade on the reduction of organophosphate flame retardants in a wastewater treatment plant,” *Chemosphere*, vol. 256, p. 126895, Oct. 2020, doi: 10.1016/j.chemosphere.2020.126895.
 - [84] L. Gao, Y. Shi, W. Li, J. Liu, and Y. Cai, “Occurrence and distribution of organophosphate triesters and diesters in sludge from sewage treatment plants of Beijing, China,” *Sci. Total Environ.*, vol. 544, pp. 143–149, 2016, <https://doi.org/10.1016/j.scitotenv.2015.11.094>.
 - [85] M. Zhong *et al.*, “Occurrences and distribution characteristics of organophosphate ester flame retardants and plasticizers in the sediments of the Bohai and Yellow Seas, China,” *Sci. Total Environ.*, vol. 615, pp. 1305–1311, 2018, <https://doi.org/10.1016/j.scitotenv.2017.09.272>.
 - [86] L. Zhang *et al.*, “Organophosphorus flame retardants (OPFRs) in the seawater and sediments of the Qinzhou Bay, Northern Beibu Gulf: Occurrence, distribution, and ecological risks,” *Mar. Pollut. Bull.*, vol. 168, p. 112368, 2021, <https://doi.org/10.1016/j.marpolbul.2021.112368>.
 - [87] Q. Shi *et al.*, “Developmental neurotoxicity of triphenyl phosphate in zebrafish larvae,” *Aquat. Toxicol.*, vol. 203, pp. 80–87, Oct. 2018, doi: 10.1016/j.aquatox.2018.08.001.
 - [88] S. Yuan, H. Li, Y. Dang, and C. Liu, “Effects of triphenyl phosphate on growth, reproduction and transcription of genes of *Daphnia magna*,” *Aquat. Toxicol.*, vol. 195, pp. 58–66, Feb. 2018, doi: 10.1016/j.aquatox.2017.12.009.
 - [89] Z. Sun, W. Ma, X. Tang, X. Zhang, Y. Yang, and X. Zhang, “Toxicity of triphenyl phosphate toward the marine rotifer *Brachionus plicatilis*: Changes in key life-history traits, rotifer-algae population dynamics and the metabolomic response,” *Ecotoxicol. Environ. Saf.*, vol. 241, p. 113731, Aug. 2022, doi: 10.1016/j.ecoenv.2022.113731.
 - [90] Q. Zhang *et al.*, “Exposure of male adult zebrafish (*Danio rerio*) to triphenyl phosphate (TPHP) induces eye development disorders and disrupts neurotransmitter system-mediated abnormal locomotor behavior in larval offspring,” *J. Hazard. Mater.*, vol. 465, p. 133332, 2024, <https://doi.org/10.1016/j.jhazmat.2023.133332>.
 - [91] Q. Huang *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.*, vol. 57, no. 9, pp. 3549–3561, Mar. 2023, doi: 10.1021/acs.est.2c05619.
 - [92] W. Fan, Z. Zhu, X. Liu, H. Zhang, Y. Qiu, and D. Yin, “Effect of nitrogen oxides and sulfur oxides to triphenyl phosphate degradation and cytotoxicity on surface of different transition metal salts,” *Sci. Total Environ.*, vol. 946, p. 174422, 2024, <https://doi.org/10.1016/j.scitotenv.2024.174422>.
 - [93] Y. Jiang, L. Yuan, Q. Lin, S. Ma, and Y. Yu, “Polybrominated diphenyl ethers in the environment and human external and internal exposure in China: A review,” *Sci. Total Environ.*, vol. 696, p. 133902, 2019, <https://doi.org/10.1016/j.scitotenv.2019.133902>.
 - [94] Y. Ren *et al.*, “A critical review of environmental remediation via iron-mediated sulfite advanced oxidation processes,” *Chem. Eng. J.*, vol. 455, p. 140859, 2023, <https://doi.org/10.1016/j.cej.2022.140859>.
 - [95] Y. Ma, W. A. Stubbings, R. Cline-cole, and S. Harrad, “Human exposure to halogenated and organophosphate flame retardants through informal e-waste handling activities - A critical,” *Environ. Pollut.*, vol. 268, no. June 2019, p. 115727, 2021, doi: 10.1016/j.envpol.2020.115727.

- [96] S. Satyam and S. Patra, "Innovations and challenges in adsorption-based wastewater remediation: A comprehensive review," *Heliyon*, vol. 10, no. 9, p. e29573, 2024, <https://doi.org/10.1016/j.heliyon.2024.e29573>.
- [97] P. R. Yaashikaa, P. S. Kumar, A. Saravanan, and D.-V. N. Vo, "Advances in biosorbents for removal of environmental pollutants: A review on pretreatment, removal mechanism and future outlook," *J. Hazard. Mater.*, vol. 420, p. 126596, 2021, <https://doi.org/10.1016/j.jhazmat.2021.126596>.
- [98] A. Nayak, B. Bhushan, and S. Kotnala, "Chapter 3 - Fundamentals and mechanism of adsorption," M. Hadi Dehghani, R. R. Karri, and I. B. T.-S. R. T. for E. P. in A. E. Tyagi, Eds. Elsevier, 2024, pp. 29–62. <https://doi.org/10.1016/B978-0-443-18618-9.00002-4>.
- [99] M. Priyadarshini, I. Das, M. M. Ghangrekar, and L. Blaney, "Advanced oxidation processes: Performance, advantages, and scale-up of emerging technologies," *J. Environ. Manage.*, vol. 316, p. 115295, 2022, <https://doi.org/10.1016/j.jenvman.2022.115295>.
- [100] F. C. Moreira, R. A. R. Boaventura, E. Brillas, and V. J. P. Vilar, "Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters," *Appl. Catal. B Environ.*, vol. 202, pp. 217–261, 2017, <https://doi.org/10.1016/j.apcatb.2016.08.037>.
- [101] Z. Yan, Y. Gu, X. Wang, Y. Hu, and X. Li, "Degradation of aniline by ferrous ions activated persulfate: Impacts, mechanisms, and by-products" *Chemosphere*. 2021 Apr;268:129237. DOI: 10.1016/j.chemosphere.2020.129237. .
- [102] R. Chen *et al.*, "Removal of triphenyl phosphate by nanoscale zerovalent iron (nZVI) activated bisulfite: Performance, surface reaction mechanism and sulfate radical-mediated degradation pathway," *Environ. Pollut.*, vol. 260, p. 113983, 2020, <https://doi.org/10.1016/j.envpol.2020.113983>.
- [103] W. Wang *et al.*, "Adsorptive removal of organophosphate flame retardants from water by non-ionic resins," *Chem. Eng. J.*, vol. 354, pp. 105–112, 2018, <https://doi.org/10.1016/j.cej.2018.08.002>.
- [104] X. Yuan *et al.*, "Removal of organophosphate esters from municipal secondary effluent by ozone and UV/H₂O₂ treatments," *Sep. Purif. Technol.*, vol. 156, pp. 1028–1034, 2015, <https://doi.org/10.1016/j.seppur.2015.09.052>.
- [105] Q. Song, Y. Feng, G. Liu, and W. Lv, "Degradation of the flame retardant triphenyl phosphate by ferrous ion-activated hydrogen peroxide and persulfate: Kinetics, pathways, and mechanisms" *Chemical Engineering Journal*, 2019, <https://api.semanticscholar.org/CorpusID:104351164>
- [106] L. Li *et al.*, "Removal of organophosphorus flame retardant by biochar-coated nZVI activating persulfate: Synergistic mechanism of adsorption and catalytic degradation," *Environ. Pollut.*, vol. 331, p. 121880, 2023, <https://doi.org/10.1016/j.envpol.2023.121880>.
- [107] Q. Song, Y. Feng, Z. Wang, G. Liu, and W. Lv, "Degradation of triphenyl phosphate (TPhP) by CoFe₂O₄-activated peroxymonosulfate oxidation process: Kinetics, pathways, and mechanisms," *Sci. Total Environ.*, vol. 681, pp. 331–338, 2019, <https://doi.org/10.1016/j.scitotenv.2019.05.105>.
- [108] Y. Yu *et al.*, "Biochar–goethite composites inhibited/enhanced degradation of triphenyl phosphate by activating persulfate: Insights on the mechanism," *Sci. Total Environ.*, vol. 858, p. 159940, 2023, <https://doi.org/10.1016/j.scitotenv.2022.159940>.
- [109] S. Tang *et al.*, "Electrochemical degradation of aromatic organophosphate esters: Mechanisms,

- toxicity changes, and ecological risk assessment,” *J. Hazard. Mater.*, vol. 480, p. 136455, 2024, <https://doi.org/10.1016/j.jhazmat.2024.136455>.
- [110] K. Valizadeh, A. Heydarinasab, S. Saeid, and S. Bazgir, “Journal of the Taiwan Institute of Chemical Engineers Preparation of modified membrane of polyvinylidene fluoride (PVDF) and evaluation of anti-fouling features and high capability in water / oil emulsion separation,” *J. Taiwan Inst. Chem. Eng.*, vol. 126, pp. 36–49, 2021, doi: 10.1016/j.jtice.2021.07.018.
- [111] W. Wang, S. Deng, D. Li, L. Ren, D. Shan, B. Wang, J. Huang, Y. Wang, G. Yu, Sorption behavior and mechanism of organophosphate flame retardants on activated carbons, *Chem. Eng. J.* 332 (2018) 286–292, <https://doi.org/10.1016/j.cej.2017.09.085>.
- [112] M. Hao, P. Gao, D. Yang, X. Chen, F. Xiao, and S. Yang, “Highly efficient adsorption behavior and mechanism of Urea-Fe₃O₄@LDH for triphenyl phosphate” *Environ Pollut.* 2020 Dec;267:114142. doi: 10.1016/j.envpol.2020.114142.
- [113] R. Hou, Y. Wang, S. Zhou, L. Zhou, Y. Yuan, and Y. Xu, “Aerobic degradation of nonhalogenated organophosphate flame esters (OPEs) by enriched cultures from sludge: Kinetics, pathways, bacterial community evolution, and toxicity evaluation,” *Sci. Total Environ.*, vol. 760, p. 143385, 2021, <https://doi.org/10.1016/j.scitotenv.2020.143385>.
- [114] X. Li *et al.*, “The genome analysis of halotolerant *Sphingobium yanoikuyae* YC-XJ2 with aryl organophosphorus flame retardants degrading capacity and characteristics of related phosphotriesterase,” *Int. Biodeterior. Biodegradation*, vol. 155, p. 105064, 2020, <https://doi.org/10.1016/j.ibiod.2020.105064>.
- [115] Y. Yu, W. Huang, W. Yu, S. Tang, and H. Yin, “Metagenomic insights into the mechanisms of triphenyl phosphate degradation by bioaugmentation with *Sphingopyxis* sp. GY,” *Ecotoxicol. Environ. Saf.*, vol. 263, p. 115261, 2023, <https://doi.org/10.1016/j.ecoenv.2023.115261>.
- [116] Y. K. N. N. N. Fukunaga, “Isolation of Aryl-Phosphate Ester-Degrading Bacterium from Leachate of a Sea-Based Waste Disposal Site” *J Biosci Bioeng.* 2004;98(6):464-9. doi: 10.1016/S1389-1723(05)00313-0..
- [117] Y. Yang, H. Yin, H. Peng, G. Lu, and Z. Dang, “Biodegradation of triphenyl phosphate using an efficient bacterial consortium GYY: Degradation characteristics, metabolic pathway and 16S rRNA genes analysis,” *Sci. Total Environ.*, vol. 713, p. 136598, 2020, <https://doi.org/10.1016/j.scitotenv.2020.136598>.
- [118] J. Wang *et al.*, “Primary biodegradation and mineralization of aryl organophosphate flame retardants by *Rhodococcus-Sphingopyxis* consortium,” *J. Hazard. Mater.*, vol. 412, p. 125238, 2021, <https://doi.org/10.1016/j.jhazmat.2021.125238>.
- [119] Y. Long, J. Wang, M. T. Nwe, X. Zou, W. Wu, and Y. Yan, “Biodegradation of aryl-organophosphate flame retardants by *Rhodococcus pyridinivorans* YC-MTN: Performance, pathway and potential in environmental remediation,” *Int. Biodeterior. Biodegradation*, vol. 190, p. 105772, 2024, <https://doi.org/10.1016/j.ibiod.2024.105772>.
- [120] M. Feng, J. Zhou, X. Yu, W. Mao, Y. Guo, and H. Wang, “Insights into biodegradation mechanisms of triphenyl phosphate by a novel fungal isolate and its potential in bioremediation of contaminated river sediment,” *J. Hazard. Mater.*, vol. 424, p. 127545, 2022, <https://doi.org/10.1016/j.jhazmat.2021.127545>.
- [121] M. Feng, J. Zhou, X. Yu, H. Wang, Y. Guo, and W. Mao, “Bioremediation of triphenyl phosphate by *Pycnoporus sanguineus*: Metabolic pathway, proteomic mechanism and biotoxicity assessment,” *J. Hazard. Mater.*, vol. 417, p. 125983, 2021, <https://doi.org/10.1016/j.jhazmat.2021.125983>.

- [122] L. Wang, X. Huang, D. J. Lim, A. K. C. Laserna, and S. F. Y. Li, "Uptake and toxic effects of triphenyl phosphate on freshwater microalgae *Chlorella vulgaris* and *Scenedesmus obliquus*: Insights from untargeted metabolomics," *Sci. Total Environ.*, vol. 650, pp. 1239–1249, 2019, <https://doi.org/10.1016/j.scitotenv.2018.09.024>.
- [123] Z.-L. Lao *et al.*, "Uptake mechanism, translocation, and transformation of organophosphate esters in water hyacinth (*Eichhornia crassipes*): A hydroponic study," *Environ. Pollut.*, vol. 341, p. 122933, 2024, <https://doi.org/10.1016/j.envpol.2023.122933>.
- [124] D. Rede, R. Vilarinho, J. A. Moreira, C. Delerue-Matos, and V. C. Fernandes, "Investigating the impact of microplastics on triphenyl phosphate adsorption in soil: Insights into environmental factors and soil properties," *Sci. Total Environ.*, vol. 944, p. 173745, 2024, <https://doi.org/10.1016/j.scitotenv.2024.173745>.
- [125] X. Dong *et al.*, "Mechanism of interaction between ascorbic acid and soil iron-containing minerals for peroxydisulfate activation and organophosphorus flame retardant degradation," *Environ. Res.*, vol. 244, p. 117883, 2024, <https://doi.org/10.1016/j.envres.2023.117883>.
- [126] X. Dong, R. Feng, Y. Jiang, T. Cai, and C. Jiang, "The impacts of temperature, soil-water ratio, and background multiplied inorganic anions on the degradation of organophosphorus flame retardants in soil by peroxydisulfate-based advanced oxidation processes" *Process Safety and Environmental Protection*, 2022, <https://api.semanticscholar.org/CorpusID:252572311>
- [127] Dong, X., Feng, R., Yang, X., Jiang, Y., Chen, L., Chen, L., Jiang, C., Cai, T., 2022. Complexation and reduction of soil iron minerals by natural polyphenols enhance persulfate activation for the remediation of triphenyl phosphate (TPHP) contaminated soil. *Chem. Eng. J.* 435, 134610. <https://doi.org/10.1016/j.cej.2022.134610>.
- [128] L. Pang, L. Ge, P. Yang, H. He, and H. Zhang, "Degradation of organophosphate esters in sewage sludge: Effects of aerobic/anaerobic treatments and bacterial community compositions," *Bioresour. Technol.*, vol. 255, pp. 16–21, 2018, <https://doi.org/10.1016/j.biortech.2018.01.104>.
- [129] L. Pang *et al.*, "Effects of biochar on the degradation of organophosphate esters in sewage sludge aerobic composting," *J. Hazard. Mater.*, vol. 442, p. 130047, 2023, <https://doi.org/10.1016/j.jhazmat.2022.130047>.
- [130] P. Wang, D. Li, X. Fan, B. Hu, and X. Wang, "Sorption and desorption behaviors of triphenyl phosphate (TPHP) and its degradation intermediates on aquatic sediments," *J. Hazard. Mater.*, vol. 385, p. 121574, 2020, <https://doi.org/10.1016/j.jhazmat.2019.121574>.
- [131] L. Xiang *et al.*, "Integrating Biochar , Bacteria , and Plants for Sustainable Remediation of Soils Contaminated with Organic Pollutants," 2022, doi: 10.1021/acs.est.2c02976.
- [132] W. Yan, L. Yan, J. Duan, and C. Jing, "Sorption of organophosphate esters by carbon nanotubes," *J. Hazard. Mater.*, vol. 273, pp. 53–60, 2014, <https://doi.org/10.1016/j.jhazmat.2014.03.030>.
- [133] S. Fan *et al.*, "Efficient removal of organophosphate esters by ligand functionalized MIL-101 (Fe): Modulated adsorption and DFT calculations.," *Chemosphere*, vol. 302, p. 134881, Sep. 2022, doi: 10.1016/j.chemosphere.2022.134881.
- [134] I. Manisalidis, E. Stavropoulou, A. Stavropoulos, and E. Bezirtzoglou, "Environmental and Health Impacts of Air Pollution: A Review.," *Front. public Heal.*, vol. 8, p. 14, 2020, doi: 10.3389/fpubh.2020.00014.

- [135] M. Cai, L. Dai, Y. Huang, Y. Xie, Y. Zhang, and Y. Wang, "Waste baijiu distillers' grains-derived biochar for efficient removal of organophosphate esters from water through adsorption," *Ind. Crops Prod.*, vol. 221, p. 119402, 2024, <https://doi.org/10.1016/j.indcrop.2024.119402>.
- [136] S. S. Jurgens *et al.*, "Mineralisation and primary biodegradation of aromatic organophosphorus flame retardants in activated sludge," *Chemosphere*, vol. 111, pp. 238–242, 2014, <https://doi.org/10.1016/j.chemosphere.2014.04.016>.
- [137] L. Zhou *et al.*, "Removal and prediction of chemicals in anaerobic–anoxic–aerobic wastewater treatment system: Case study on organophosphates," *Emerg. Contam.*, vol. 10, no. 4, p. 100344, 2024, <https://doi.org/10.1016/j.emcon.2024.100344>.
- [138] K. Wei, H. Yin, H. Peng, G. Lu, and Z. Dang, "Bioremediation of triphenyl phosphate by *Brevibacillus brevis*: Degradation characteristics and role of cytochrome P450 monooxygenase.," *Sci. Total Environ.*, vol. 627, pp. 1389–1395, Jun. 2018, doi: 10.1016/j.scitotenv.2018.02.028.
- [139] K. Wei, H. Yin, H. Peng, G. Lu, and Z. Dang, "Bioremediation of triphenyl phosphate in river water microcosms: Proteome alteration of *Brevibacillus brevis* and cytotoxicity assessments," *Sci. Total Environ.*, vol. 649, pp. 563–570, 2019, <https://doi.org/10.1016/j.scitotenv.2018.08.342>.
- [140] A. Debroy, J. S. Saravanan, M. J. Nirmala, M. Pulimi, and A. Mukherjee, "Algal EPS modifies the toxicity potential of the mixture of polystyrene nanoplastics (PSNPs) and triphenyl phosphate in freshwater microalgae *Chlorella* sp.," *Chemosphere*, vol. 366, p. 143471, 2024, <https://doi.org/10.1016/j.chemosphere.2024.143471>.
- [141] R. Hou, X. Luo, C. Liu, L. Zhou, J. Wen, and Y. Yuan, "Enhanced degradation of triphenyl phosphate (TPHP) in bioelectrochemical systems: Kinetics, pathway and degradation mechanisms," *Environ. Pollut.*, vol. 254, p. 113040, 2019, <https://doi.org/10.1016/j.envpol.2019.113040>.
- [142] J. Cristale, R. F. Dantas, A. De Luca, C. Sans, S. Esplugas, and S. Lacorte, "Role of oxygen and DOM in sunlight induced photodegradation of organophosphorous flame retardants in river water," *J. Hazard. Mater.*, vol. 323, pp. 242–249, 2017, <https://doi.org/10.1016/j.jhazmat.2016.05.019>.
- [143] L. Feng *et al.*, "Oxygen vacancies-enriched spent lithium-ion battery cathode materials loaded catalytic membrane for effective peracetic acid activation and organic pollutants degradation," *J. Hazard. Mater.*, vol. 480, p. 136444, 2024, <https://doi.org/10.1016/j.jhazmat.2024.136444>.
- [144] Y. Deng, H. Zhao, X. Zhang, X. Li, and G. Chi, "The dissipation of organophosphate esters mediated by ryegrass root exudate oxalic acid in soil: Analysis of enzymes activities, microorganism" *Chemosphere*. 2024 May;356:141896. doi: 10.1016/j.chemosphere.2024.141896. .
- [145] X. Dong, X. Yang, S. Hua, Z. Wang, T. Cai, and C. Jiang, "Unraveling the mechanisms for persulfate-based remediation of triphenyl phosphate-contaminated soils: Complicated soil constituent effects on the formation and propagation of reactive oxygen species" *Chemical Engineering Journal*. 426. 130662. 10.1016/j.cej.2021.130662..
- [146] C.-Y. Chen, Y.-H. Liu, C.-H. Chieh, and W.-H. Chang, "Fast and Environment-Friendly GC-MS Method for Eleven Organophosphorus Flame Retardants in Indoor Air, Dust, and Skin Wipes.," *Toxics*, vol. 9, no. 12, Dec. 2021, doi: 10.3390/toxics9120350.
- [147] X. Wang *et al.*, "Determination of Organophosphate Esters in Water Samples Using Gas

- Chromatography–Mass Spectrometry (GC–MS) and Magnetic Solid-Phase Extraction (SPE) Based on Multi-Walled Carbon Nanotubes (MWCNTs),” *LCGC North Am.*, vol. 40, pp. 262–269, 2022, [Online]. Available: <https://www.chromatographyonline.com/view/determination-of-organophosphate-esters-in-water-samples-using-gas-chromatography-mass-spectrometry-gc-ms-and-magnetic-solid-phase-extraction-spe-based-on-multi-walled-carbon-nanotubes-mwcnts->
- [148] B. Kowalski and M. Mazur, “The Simultaneous Determination of Six Flame Retardants in Water Samples Using SPE Pre-concentration and UHPLC-UV Method.,” *Water. Air. Soil Pollut.*, vol. 225, no. 3, p. 1866, 2014, doi: 10.1007/s11270-014-1866-4.
 - [149] M. A. Babich, “Risk assessment of low-level chemical exposures from consumer products under the U.S. Consumer Product Safety Commission chronic hazard guidelines.,” *Environ. Health Perspect.*, vol. 106 Suppl 1, no. Suppl 1, pp. 387–390, Feb. 1998, doi: 10.1289/ehp.98106s1387.
 - [150] M. K. Trivedi, A. Branton, D. Trivedi, G. Nayak, K. Bairwa, and S. Jana, “Physicochemical and Spectroscopic Characterization of Biofield Treated Triphenyl Phosphate,” vol. 3, no. 5, pp. 168–173, 2015, doi: 10.11648/j.ajac.20150305.13.
 - [151] U. Lahl and B. Zeschmar-Lahl, “Risk based management of chemicals and products in a circular economy at a global scale (risk cycle), extended producer responsibility and EU legislation,” *Environ. Sci. Eur.*, vol. 25, no. 1, p. 3, 2013, doi: 10.1186/2190-4715-25-3.



DSPACE

<https://dspace.org/>

From contamination to remediation: understanding the toxicity, risk assessment, and degradation pathways of triphenyl phosphate and related organophosphate flame retardants in water and soil

Vasanthiya Tej, A.; Pranika, M.; Adhithya, S.; Nithya, Kamaraj; Sathish, Asha ...

2025-10-15

Elsevier

<https://doi.org/10.1016/j.scitotenv.2025.180356>

Vasanthiya Tej A, Pranika M, Adhithya S, et al., (2025) From contamination to remediation: understanding the toxicity, risk assessment, and degradation pathways of triphenyl phosphate and related organophosphate flame retardants in water and soil. Science of The Total Environment, Volume 999, October 2025, Article number 180356