Water Practice & Technology

 Water Practice & Technology Vol 19 No 3, 937 doi: 10.2166/wpt.2024.031

Research progress of persistent organic pollutants in water: classification, sources, potential risks, and treatment approaches

Aindrila Mandal[a], P. Senthil Kumar[b,*], Cumbakonam Sampathkumar Poorva[a], Lohita Srinivasa Raju[a], Senthil Rathi Balasubramani[c] and Gayathri Rangasamy[d,e]

[a] Department of Chemical Engineering, Sri Sivasubramaniya Nadar College of Engineering, Chennai 603110, India
[b] Centre for Pollution Control and Environmental Engineering, School of Engineering and Technology, Pondicherry University, Kalapet, Puducherry 605014, India
[c] Department of Bioengineering, Institute of Biotechnology, Saveetha School of Engineering, Saveetha Institute of medical and technical Sciences, Saveetha University, Chennai 602105, India
[d] School of Engineering, Lebanese American University, Byblos, Lebanon
[e] University Centre for Research and Development & Department of Civil Engineering, Chandigarh University, Gharuan, Mohali, Punjab 140413, India
*Corresponding author. E-mail: senthilkumarp@pondiuni.ac.in

PSK, 0000-0001-9389-5541

ABSTRACT

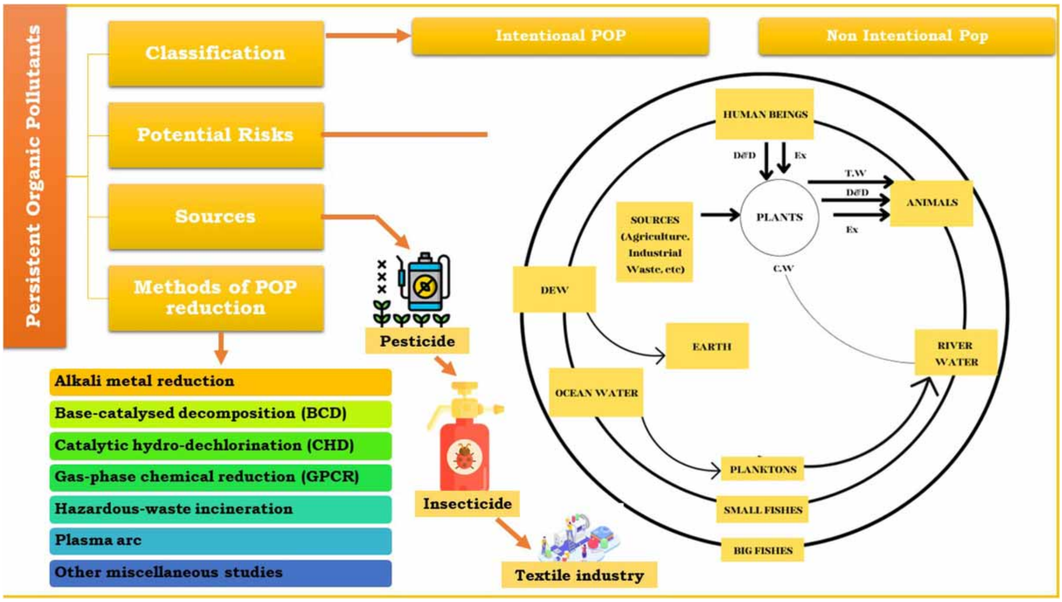
The occurrence of persistent organic pollutants (POPs) in almost every sphere of life and their notorious effects have been a global concern for quite a few decades, regardless of the fact that notable conventions have banned the standard POPs. Control measures and numerous technologies are being researched, but still exhibits challenges to completely curb these chemicals' destructive effects. The negative impacts of the POPs in terms of environmental and human health are a growing concern. In recent years, studies have proven that the list of POPs keeps increasing, and their concentrations levels are widely varied region wise. The current review presents sources and classification of POPs. Furthermore, the deleterious consequences due to POPs on environment and human health have been illustrated. A few potential methodologies that can be implemented to control the hazardous effects of POPs have been discussed.

Key words: persistent organic pollutant, POPs reduction approaches, sources, wastewater treatment

HIGHLIGHTS

- Intentional and unintentional persistent organic pollutants (POPs) were discussed.
- Sources and impact of POPs has been reviewed.
- Effects of POPs on environment and human beings were explored.
- Different methods for the POPs reduction were elucidated.

GRAPHICAL ABSTRACT



1. INTRODUCTION

During the surge of industrialisation, post-World War II, the wide usage of persistent organic pollutants (POPs) has begun. These synthetic chemicals were cheaper than their natural predecessors, and hence, POPs were introduced into commercial use for economy's benefit (Duttagupta *et al.* 2020b). They proved efficient in pest and disease control, agriculture, industry, etc. Since POPs survive for a long time in the biosphere and transmit from one species to another via the food chain, they have a severe unfortunate effect that has been endangering human health and the ecosystem for decades (Boulkhessaim *et al.* 2022). POPs are hazardous chemical substances that have recently received a lot of attention internationally. These chemicals possess specific physical and chemical properties that enable them to bioaccumulate, resist degradation, and travel long distances. Polychlorinated biphenyls (PCBs), dichloro-diphenyl-trichloroethane (DDT), and dioxins are some of the most well-known POPs. POPs have been quantified in every continent and significant climate (Fitzgerald & Wikoff 2014).

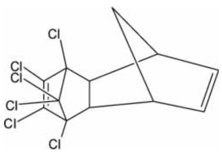
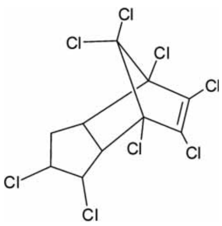
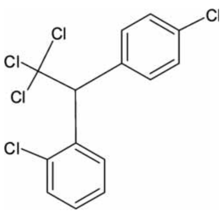
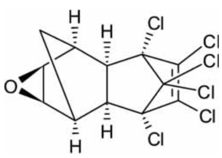
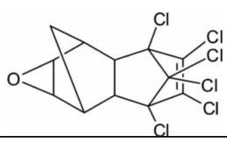
Persistence, toxicity, bioaccumulation, and long-distance transport are the four basic properties of POPs. Due to their resistance to numerous environmental processes, including chemical, biological, and photolytic destruction, POPs last for a long time. They are poor in water solubility and high in lipid solubility (hence the term 'lipophilic'), which causes them to bioaccumulate in fatty tissues of living beings (Fitzgerald & Wikoff 2014). As a result, the food chain is biomagnified. Therefore, the highest POP concentrations are found in creatures at the top of the food chain and are typically present everywhere in the environment and biota, including humans (Fernandez *et al.* 2007). Through a process known as the 'grasshopper effect,' their semi-volatility makes it easier for them to fly over vast distances in the air or absorb into airborne or waterborne particulate matter (Liu *et al.* 2023).

Every living species, including humans, carry a certain amount of POPs in their bodies near or at the danger level. Even the smallest amount of POPs can threaten animal and human tissues, lead to cancers, damage the nervous system, cause immune system diseases, and cause reproductive and developmental disorders (Mishra *et al.* 2022). Exposure to POPs has been linked to a number of ecotoxicological outcomes, including immunotoxicity, dermal impacts, congenital impairments, cancer, decreased reproductive function, and population decreases in general. Numerous wildlife species suffer immunodeficiencies as a result of specific POPs, including PCBs, chlordane, hexachlorobenzene (HCB), dioxins, toxaphene, and DDT (Lee *et al.* 1998; Devi 2020). Exposure to POP also causes reproductive problems in mink, and population declines in porpoises, dolphins, seals, and beluga whales. Humans experience a wide range of health impacts from genotoxicity to reproductive abnormalities, immune system changes, elevated cancer risk, endocrine disruption, neurobehavioural impairment, and increased birth defects when exposed to even low amounts of POPs. POPs can be passed from mothers to their unborn children through the placenta and through breast milk in mammals, including humans. It is important to remember, though, that breastfeeding has benefits that outweigh the alleged concerns.

Many different combustion processes, including those used in power plants, industrial boilers, furnaces, incinerators, and home heating equipment, are thought to produce POPs. Full-scale combustion facilities have the potential to be significant POP generators due to the massive mass flow of flue gas released by a plant. Total POP emissions from small combustion appliances like wood stoves and home oil furnaces can also be significant due to the enormous number of installed units close to highly inhabited areas (Lee *et al.* 1998; Adithya *et al.* 2021).

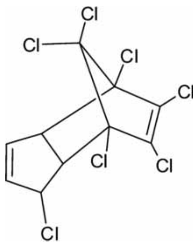
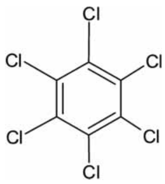
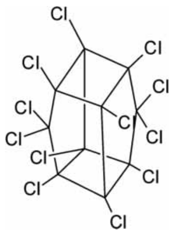
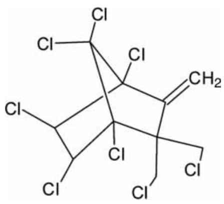
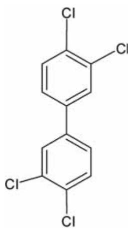
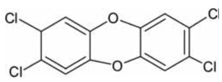
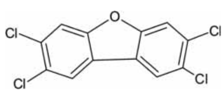
Around 90 nations, including the European Union, joined forces to create the historic Stockholm Convention in May 2001 to address the problem of POPs. There are now 179 parties in the convention. Twelve main POPs, often referred to as the 'Dirty Dozen', are included in Table 1 and are subject to reduction or eradication under this treaty (Fitzgerald & Wikoff 2014). These include polychlorinated-dibenzo-p-dioxins (PCDDs), PCBs, polychlorinated dibenzofurans (PCDFs), toxaphene, aldrin, endrin, DDT, chlordane, dieldrin, mirex, heptachlor, and HCB. Since then, tributyltin and carcinogenic polycyclic aromatic hydrocarbons (PAHs) have been included (Fernandez *et al.* 2007; El-Shahawi *et al.* 2010). The convention imposes obligations on parties, including conducting research, locating POP-contaminated areas, identifying POP-contaminated areas, limiting and eradicating the manufacture and use of POPs, and providing financial support and incentives for the convention. Before becoming a party, a state or regional economic integration organisation must submit to the depositary a method of certification, acceptance, approval, or accession. POPs were known to be both a blessing and a curse, with the latter eventually outweighing the former. We will conduct a thorough analysis of POPs and their classifications in this article, as well as their sources, characteristics, impacts on the environment and living things throughout the world, mitigation strategies, and so on.

Table 1 | Compound diagram, uses and effects of dirty dozen introduced by the Stockholm Convention

Sl no.	Name of the compound	Compound diagram	Main uses	Environmental effects	References
1	Aldrin		Pesticides	Easily converted to dieldrin	Fitzgerald & Wikoff (2014)
2	Chlordane		Insecticides	Slow environmental degradation	Fitzgerald & Wikoff (2014)
3	DDT		Pesticides	Bioaccumulation in water	El-Shahawi *et al.* (2010)
4	Dieldrin		Control termites and textile pests	Effects on the nervous system, liver, and immunity in animals	Nowak *et al.* (2019)
5	Endrin		Insecticides	Soil contaminant and slow degradation	Marshall *et al.* (2002)

(*Continued.*)

Table 1 | Continued

Sl no.	Name of the compound	Compound diagram	Main uses	Environmental effects	References
6	Heptachlor		Control soil insects and termites	Toxic to aquatic animals and can bioaccumulate in fish and freshwater invertebrates	Nizzetto *et al.* (2010)
7	Hexachlorobenzene		Fungicide	Persistence in the environment, potential to bioaccumulate, and toxicity to humans and the environment	Tanabe *et al.* (1987)
8	Mirex		Control fire ants	Damage to aquatic life	Nizzetto *et al.* (2010)
9	Toxaphene		Insecticide and control tics and mites in livestock	Gets accumulated in fatty tissues of various organisms	Parra-Arroyo *et al.* (2022)
10	PCBs		Heat exchange fluids in capacitors, additives in paints	Carcinogen in humans and various other organisms	Weber *et al.* (2018); Lau *et al.* (2017)
11	PCDDs		Unintentionally formed	Extremely stable in the environment and can bioaccumulate in fatty tissues	Eduljee & Dyke (1996)
12	PCDFs		Unintentionally formed	Extremely stable in the environment and can bioaccumulate in fatty tissues	Eduljee & Dyke (1996)

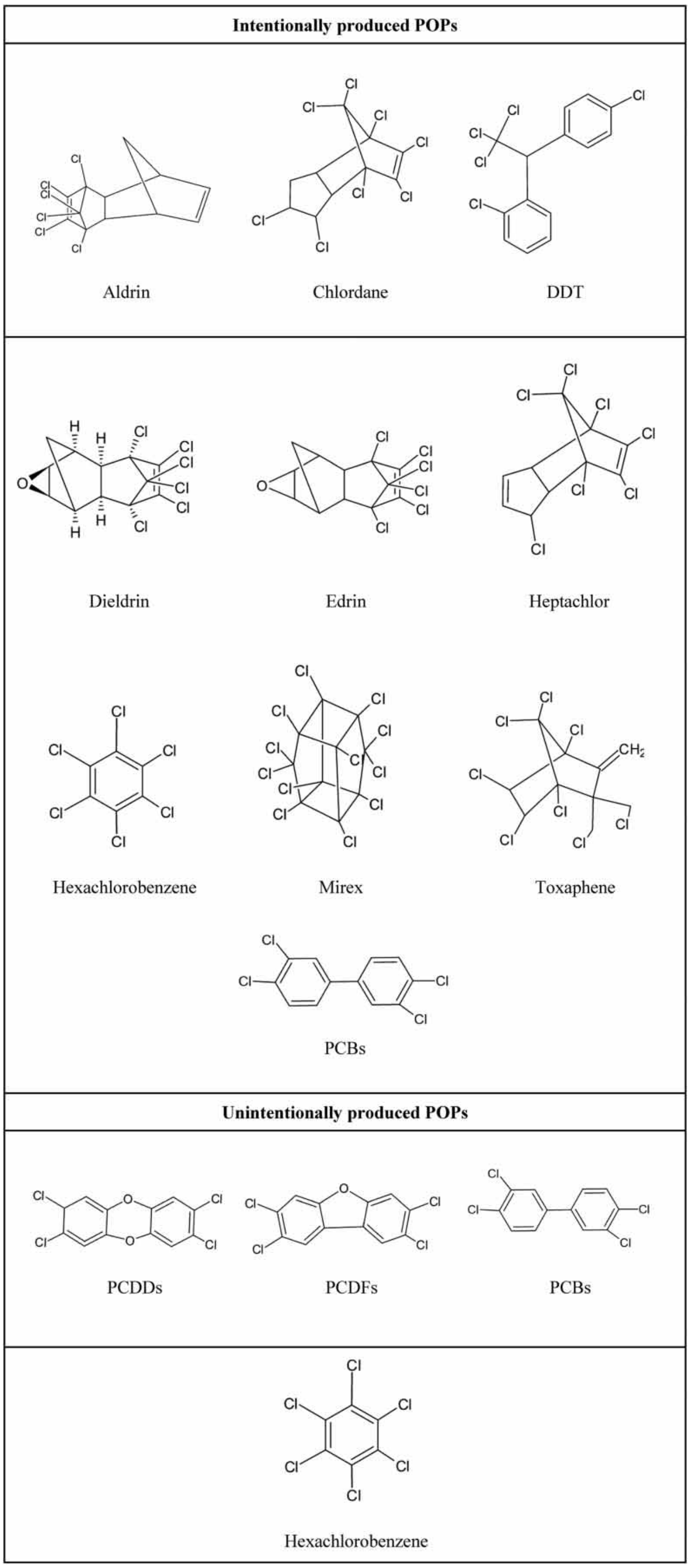
2. CLASSIFICATION OF POPS

POPs are hazardous organic compounds that take an extended period to break down naturally in the atmosphere and can build up in living things and ecosystems. Because of POPs' durability in ecosystems, biological magnification, and biological accumulation in ecosystems, as well as their serious adverse impacts on human health, there are substantial worries about them at the global level. POPs are divided into three different groups – pesticides, chemicals used in industry, and unintentional creation (Nguyen *et al.* 2020; Tang 2021).

2.1. Intentional POPs

The two categories of POPs, intentional and unintentional, are outlined in Table 2 (Kodavanti *et al.* 2014). Intentional POPs consist of pesticides and industrial chemicals, whose prolonged usage harm the surroundings. Some

Table 2 | Chemical structure of intentional and unintentional POPs



of them are PCBs, hexachlorobenzenes (HCB)s, aldrin, mirex, and furans. POPs were developed around the early 1920s. With the boom in the industrial sector, after World War II, commercially useful POPs began to see a global distribution. POPs boosted crop productions too, conquering the agricultural industry. However, the manufacturing and agricultural sectors did not start to rely substantially on POPs until the 1940 and 1950s (Kodavanti *et al.* 2014).

2.1.1. Pesticides

Pesticides have most positively affected the economy; however, when it is over the permissible limits, they are said to have adverse effects on various environmental aspects and humans due to their pervasive manifestation and toxicity. Therefore, efforts should be made to mitigate pesticide residues by employing effective detection properly (Parra-Arroyo *et al.* 2022). Some of the most commonly used pesticides are PCBs, pentachlorophenol, dioxins (dibenzofurans), DDT, HCB, mirex, aldrin, chlordane, and toxaphene.

Methods like chromatography and mass spectrometry have proven to be useful in detecting pesticides (Stachniuk & Fornal 2015; Pang *et al.* 2016); however, metal–organic frameworks (MOFs) are considered to be quite effective in detecting POPs. In MOFs, ligands are linked metal ions or clusters that create three-dimensional structures (Vikrant *et al.* 2018). MOFs with well-defined structures, crystalline structure, and comparatively high porosity may reach upward of 7,000 m^2/g in some cases (Farha *et al.* 2012).

2.1.2. Industrial-use chemicals

Some industrial chemicals that heavily contribute to pollution are perfluorinated compounds, polybrominated diphenyl ethers (PBDEs), DDT, and PCBs. These chemicals have adverse effects on wildlife due to the discharge of chemicals into streams, rivers, and lakes, which often leads to bioaccumulation of toxins in the upper-trophic level predators through the food chain (Karthigadevi *et al.* 2021; Qiao & Xiong 2021). Higher concentrations of POPs found in food have chronic adverse health effects, including cancer, neurotoxicity, disruption of the endocrine system, and damage to the developing foetus (Chen *et al.* 2021; Tripathi *et al.* 2022).

2.2. Unintentional POPs

Unintentionally produced POPs (UP-POPs) are unwanted by-products produced during chemical processes. Unintentional POPs are volatile and toxic and cause health hazards. Some commonly traced UP-POPs are HCB, PCDF, PCBs, and PCDDs (Kodavanti *et al.* 2014). Polychlorinated naphthalenes are a separate class of POPs that can develop through a variety of processes and thermal procedures (Odabasi *et al.* 2017; Weber *et al.* 2018). Iron ore sintering, municipal waste incineration, and materials that come into contact with food are the main sources of UP-POPs (Tuppurainen *et al.* 1998; Winkler 2015; Shen *et al.* 2021).

3. SOURCES

The sources can be broadly classified into primary and secondary sources. The term ‘primary sources’ describes sources whose emission levels are controllable. The secondary sources, also called re-emissions, are those whose emission levels cannot be controlled. These sources are described in detail in the following sections.

3.1. Primary sources

Primary sources produce POPs intentionally for one or more goals, unintentionally as by-products of industrial operations, or accidentally in response to human action (Breivik *et al.* 2004).

3.1.1. Pesticides

From the dirty dozen POPs named by the Stockholm Convention initially, nine of them are pesticides. They are HCB, dieldrin, aldrin, heptachlor, DDT, endrin, mirex, and chlordane. These pesticides are used because they are stable chemically in ecological conditions. Pesticides, like toxaphene congeners, have a half-life of 14 years, and some were found as residues in water more than a decade after they had been banned. Banned and obsolete pesticides have been used, contributing to the emission levels of POPs in water bodies, which Food and Agriculture Organisation (FAO) recognizes as a significant global issue. Due to their proximity to human activities, the pesticides are of great concern in bays and harbours. POP levels must be monitored by sticking to the limits prescribed for groundwater, fishery water, drinking water, and seawater (Hu *et al.* 2007).

3.1.2. Industrial chemicals

PCBs and PBDEs are the key representatives of industrially produced POPs. Although PCBs have peaked in the past, PBDEs have been produced in high volumes in recent years. HCB was also intentionally created until the Stockholm Convention banned it (Rashed & Summers 2022).

3.1.3. Unintentional by-products

The most common POPs, produced unintentionally, are PCDDs and PCDFs. Currently, the emission and concentration levels cannot be appropriately estimated due to the diversity in production and usage. However, certain reliable sources can be listed, including clinical waste, emissions from sinter factories, iron and steel industries, non-ferrous metal processes, and coal combustion (Shen *et al.* 2021).

3.1.4. Miscellaneous sources

HCB is considered to be a miscellaneous POP. Due to its thermodynamic stability, HCB is generated in tiny amounts in various reactions where it persists. In manufacturing numerous chlorine-containing insecticides, for instance, residues of HCB are generated during the chlorination stage. HCB is also produced in high-energy reactions combining chlorine and graphite-like compounds like soot (Fenstad *et al.* 2016).

3.2. Secondary sources

More studies are needed to enhance the quantifiable knowledge of the comparative significance of primary emissions versus re-emissions for numerous POPs, even though the perceived significance of primary emissions versus re-emissions into the atmosphere for POPs has indeed been mentioned in a variety of studies. For certain POPs, it is necessary to consider the relative significance of natural emissions in respect to the regional and global mass balance. The PCDD/Fs provide as helpful examples from this perspective. In the instance of PCDD/Fs, a growing number of data suggest that dioxins have likely been found in the environment for much longer than the beginning of the 'chlorine business.' The multimedia component of chemical release may be crucial for assessing the overall ecological consequences of such chemicals under specific circumstances and for the highly volatile POPs. For example, industrial wastewaters directly release some volatile substances into aquatic habitats. These compounds might subsequently vaporize out of the aqueous solution into the environment. Further ambient dosage estimations out of which patterns can be inferred are required, in addition to the obvious need for enhanced emission characterisation, to make comparisons with simulations and act as a checking on emission data. The ultimate objective is to enhance and safeguard the environment that all people live in (Kallenborn *et al.* 2013). Over the years, newly identified POPs have been added to the list, which had originally consisted of 12 POPs. Among these chemicals are a few that have been detected in freshwater regions. Table 3 comprises the research on POPs found in the water of several regions globally. The chemicals listed are either identified as POPs or potential POPs.

4. POTENTIAL RISKS

Because of their propensity to accumulate bioaccumulative over time, POPs are known as the silent killers. They can be found in all parts of our surroundings, including in humans, animals, and plants. These are the cause of several deadly illnesses and environmental issues. POPs are linked to a variety of disorders, including obesity, diabetes, cancer, hormonal imbalances, heart disease, issues with reproduction, and environmental issues (Alharbi *et al.* 2018). The most prevalent POPs are mirex, dioxins, PCBs, polychlorinated dibenzodioxins (PCDDs), PBDEs, PCDFs, HCB, and chlorinated hydrocarbons, such as aldrin, DDT, endrin, and dieldrin. These can be found in a wide range of goods and products, such as flame retardants, wood floor finishes, hydraulic fluids, adhesives, coatings for electrical wiring and electronic components made of polyvinyl chloride, foams, paints, computers, textiles, televisions, furniture, and cars, as well as industrial and commercial surfactants (Islam *et al.* 2018). The main pollutants that cause POP contamination include dioxins, dibenzofurans, PAHs, organochlorine pesticides (OCPs), and PCBs. Since these substances are not biodegradable, they stay in the environment abnormally intact for extended periods of time. Furthermore, the long-range transport, persistence, and propensity for biological accumulation of these chemicals make them extremely concerning. Once they go into the food chain, they develop in the body's fatty tissue and have the potential to have a negative impact on both the environment and human health (Gaur *et al.* 2018).

Table 3 | Concentrations of POPs in different types of water sources

Type of water sources	POP	Concentrations of POP	Reference
Surface water	Polycyclic aromatic hydrocarbons	6,212 ng/dm^3	Pawlak *et al.* (2019)
Surface water	Polychlorinated biphenyls	273 ng/dm^3	Pawlak *et al.* (2019)
Industrial soil	Dieldrin	24.0 ng/g	Buser *et al.* (2009)
Industrial soil	Aldrin	0.2 ng/g	Buser *et al.* (2009)
River	Dieldrin	0.99 ± 0.33 μg/kg	Pang *et al.* (2022)
River	Aldrin	75.31 ng/L	Pang *et al.* (2022)
Soil	Dieldrin	0.018 mg/kg	Tsiantas *et al.* (2021)
Surface water	Aldrin	0.736 ng/L	Liu *et al.* (2020)
Surface water	Heptachlor	0.426 ng/L	Liu *et al.* (2020)
Surface water	Endrin	0.063 ng/L	Liu *et al.* (2020)
Drinking water	Aldrin	0.047 ppb	Panis *et al.* (2022)
Drinking water	Dieldrin	0.047 ppb	Panis *et al.* (2022)
Drinking water	DDT	0.07 ppb	Panis *et al.* (2022)
Drinking water	Chlordane	0.181 ppb	Panis *et al.* (2022)
Drinking water	Lindane	2.17 ppb	Panis *et al.* (2022)
Sediment	DDT	1.58–51.0 ng/g	Peng *et al.* (2020)
Porewater	DDT	66.3–250 ng/L	Peng *et al.* (2020)
Rivers	DDT	0.9669 ± 0.2994 μg/L	Nyaundi *et al.* (2023)
Surface water	Aldrin	2–37 μg/L	Oginawati *et al.* (2021)
Sediment	Aldrin	2–1,438 μg/L	Oginawati *et al.* (2021)
Mollusks	DDT	13–2,758 μg/L	Oginawati *et al.* (2021)
Mollusks	Heptachlor	13–2,758 μg/L	Oginawati *et al.* (2021)
Fish	DDT	11–104 μg/L	Oginawati *et al.* (2021)
Fish	Heptachlor	11–104 μg/L	Oginawati *et al.* (2021)
Air	Hexachlorobenzene	0–460 pg/m^3	Tu *et al.* (2022)
Natural water	Hexachlorobenzene	0.52–12,200 ng/L	Tu *et al.* (2022)
Sediments	Hexachlorobenzene	0.08–55 ng/g	Tu *et al.* (2022)
Sediments in river	Polychlorinated biphenyls	28 pg/g	Johansen *et al.* (2021)
Sediments in river	Hexachlorobenzene	16–100 pg/g	Johansen *et al.* (2021)
Sediments in sea	Polychlorinated biphenyls	630–880 pg/g	Johansen *et al.* (2021)
Sediments in sea	Hexachlorobenzene	530–770 pg/g	Johansen *et al.* (2021)

POPs poison food, water, and other organisms higher up in the food chain, including humans, polar bears, killer whales, and eagles. There is proof that a large number of individuals globally may currently have enough POPs in their body fat, where they can build up and have a major negative impact on health that can result in disease and even death. In recent years, some POPs have also been linked to decreased immunity in young children and adults, as well as to an increase in infections at the same time. They have also been linked to developmental abnormalities, neurobehavioural impairment, malignancy, and the induction or promotion of tumours and cancer. Certain POPs are also thought to be significant risk factors in the development of breast cancer in humans. When POPs are taken at a younger age, there can be serious side effects, including birth defects, cancer, multiple tumours, immune system disorders, reproductive issues, decreased resistance to disease, stunted growth, and long-term impairment of brain function (El-Shahawi *et al.* 2010).

4.1. Effects on the environment

The interrelationship between air, water, animals, and people in the environment is intricate. Directly or indirectly, these identities' consequences harm the ecosystem. POPs consequently interfere with biotic, abiotic, social, cultural, and technical aspects of the environment. The natural balance is upset by POP pollution, putting the ecosystem and the welfare of all living creatures in peril. POPs build up in aquatic animals, causing them to die. As a result, there is a disparity in the ecology of the sea. POPs often last more than 20 years in the environment, with a few lasting a century. HCB, DDT, PCDDs, endrin, furans, and mirex can last 10–20 years in the environment. The grasshopper effect, which involves cyclic volatilisations and condensations, is visible in POPs. These chemicals relocate to cooler regions from warmer ones. When the temperature drops, these settle down, but when the temperature rises, they evaporate. This cyclic movement of POPs might sometimes affect global warming (Everaert & Baeyens 2002; Altarawneh *et al.* 2009).

Concentrations of POPs are typically lower in the polar climates than in warm climates. While some POPs (such as PCBs and DDTs) are declining, other POPs (such as fluorinated and brominated flame retardants) are growing in polar animals. The rise in global production and usage of these pollutants is the primary cause of this rise. Concentrations of POPs in glaucous gulls, canines, and grizzly bears from these regions have been demonstrated through laboratory and field research to exceed the impact thresholds, suggesting that the current POP levels alter behavioural, biochemical, physiological, and immunological variables (Ismail *et al.* 2018).

POPs find their way into everything through unintended activities, channels, and processes. POPs take a long time to degrade, and present international control mechanisms are sluggish and inefficient; generally, the world is better without them (Zhu & Kang 2014). This suggests that chemical management must be prescriptive and risk-averse from the start. Figure 1 illustrates the transport pathways of POPs through various media in the environment. Given the toxicological/ecotoxicological and public health risks raised by POPs, these compounds should not be permitted into our environment (Marshall *et al.* 2002).

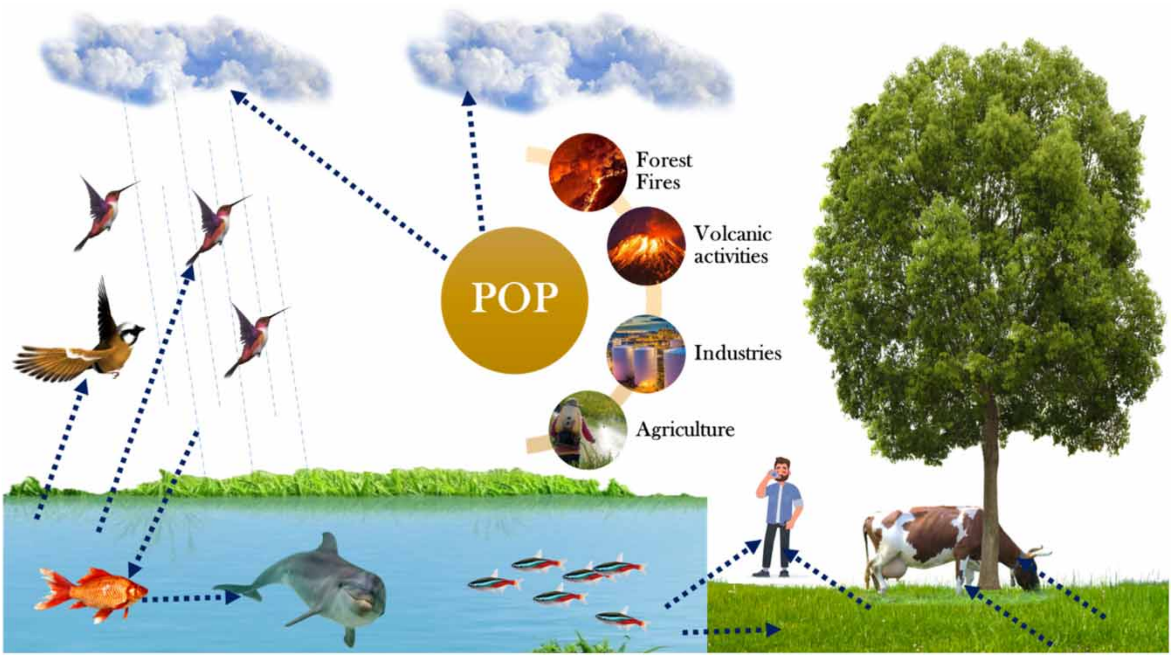


Figure 1 | Pathway of POPs on the environment.

4.2. Health hazards

A vast variety of contaminants has always polluted our globe. Organic pollutants that are resistant to degradation are known as persistent pollutants for an extended period of time despite being resistant to environmental deterioration (Ritter *et al.* 1995). POPs are divided into intentional POPs and unintentional POPs. They are in charge of biomagnification because the toxins build up and are transferred via the food web to the animals at higher trophic levels. As a result, it may be claimed that everyone in the current situation has POPs in their bodies. Recent studies have discovered POPs in foetuses and embryos as well. Exposure to these POPS results in a number of health problems, including obesity, cancer, cardiovascular disease, diabetes, and hormone disruption. The United States Environmental Protection Agency (EPA) states that PCBs are the most dangerous POPs and that dioxins are the toxic POPs that cause cancer (Tanabe *et al.* 1987; Safe 1990). The following sections highlight a few health issues related to POPs.

4.2.1. Endocrine or hormone disruption

Endocrine-disrupting chemicals, commonly referred to as POPs, are compounds that mimic various hormones and interfere with their function, leading to a variety of disorders such as diabetes, reproductive problems, and stunted growth (Jacobson *et al.* 1990a, 1990b; Alharbi *et al.* 2018). These substances attach to proteins, which interferes with hormone function (Predieri *et al.* 2020). These substances contain c-halogen molecules that can withstand various types of degradation (Gonsioroski *et al.* 2020; Dichiarante *et al.* 2021), such as PCBs, phthalates, PBDEs, dioxins, and pesticides. From conception until death, the body's biological activities are regulated by the endocrine system, according to the research by Nowak *et al.* (2019), Yilmaz *et al.* (2020), and Dahiya *et al.* (2021). Development, growth, and maturation are controlled by the endocrine system (Street & Bernasconi 2020; Dahiya *et al.* 2021). Pesticides, fungicides, and other chemicals frequently result in endocrine disruption. Substances that interact with the hormone system are known as 'endocrine disruptors' which frequently have harmful consequences on the body, including weight gain, sluggish reflexes, and impaired visual recognition that are visible from an early age (Street & Bernasconi 2020).

4.2.2. Cancer

White blood cell development that is out of the ordinary leads to the condition known as cancer. Cancer is a fatal illness that poses a threat to life because it accounts for 21% of fatalities worldwide (Ali *et al.* 2011). Different malignancies occur due to higher POP distribution in low-density lipoproteins, including PCDDs, PBDEs, PCBs, and dibenzofurans (PCDD/Fs) (Ljunggren *et al.* 2014). The existence of these POPs in marine life is caused by biomagnification. Therefore, eating seafood raises your risk of developing cancer.

4.2.3. Obesity

Obesity is a disorder involving excessive fat, which might lead to other complications (Chaput *et al.* 2012). Other complications associated with obesity are osteoarthritis and cardiovascular diseases (Thayer *et al.* 2012). The United States has the highest rate of obesity, close to 74%. A few reviews are based on the role of POPs in obesity (Hectors *et al.* 2011; Myre & Imbeault 2014). However, a positive correlation was found between endocrine disruption and POPs, leading to obesity, which is one of the complications of endocrine disruption. When gene expression levels of obesity markers were evaluated, it was found that PCBs were a major contributing factor to obesity (Pereira-Fernandes *et al.* 2014).

4.2.4. Cardiovascular diseases

It is a disease that impacts the blood vessels or the heart. About 17 million people per year pass away from cardiovascular illness, with hypertension accounting for one-third of these deaths. Cardiovascular disorders are one of the leading causes of mortality (Alharbi *et al.* 2018). The four most typical cardiovascular conditions are arrhythmia, excessive blood pressure, cardiac arrest, and coronary heart disease. Since POPs are known to be lipophilic, the majority of them accumulate in the body and cause cardiovascular problems by biomagnification (Ljunggren *et al.* 2014). POPs including PCBs, polybrominated biphenyl, and organochlorine insecticides cause cardiovascular disorders. High levels of dioxins and PCBs were found to be associated with hypertension, elevated triglycerides, and hyperglycaemia.

4.2.5. Diabetes

When the pancreas either produces insufficient amounts of insulin or is unable to utilise the insulin that is produced, it results in a persistent illness called diabetes. The two most common types of diabetes are type 1 and type 2 diabetes. The pancreas produces very little or no insulin, which leads to type 1 diabetes. On the other hand, type 2 diabetes affects the way body produces insulin. Stroke, heart disease, kidney failure, foot gangrene are long-term effects of diabetes. Bioaccumulation of POPs in humans leads to the emergence of diabetes as well. The development of the metabolic syndrome has been directly attributed to PCBs and chlorinated pesticides. In addition, a link was established between dioxins and metabolic syndrome. According to the authors, type 2 diabetes is about 1.6–2.25 times more prevalent when POP concentrations are high. Moreover, it was shown that connections between type 2 diabetes and the chemicals trans-nonachlor and oxychlordane were significantly higher in obese people. It was assessed whether PCBs and a number of other chemicals increased the likelihood of developing diabetes (Carpenter 2008). The National Health and Nutrition Examination was used by two distinct parties to conduct a survey on a random sample of American inhabitants. It was determined that these POPs are main reasons for developing diabetes in people. According to research, the precise mechanism is unknown due to its complexity, but it is conceivable that these POPs could change how much insulin is produced.

5. METHODS FOR PERSISTENT ORGANIC POLLUTANTS REDUCTION

The wastes produced by numerous industrial operations, the production of chemicals, and their by-products all contain POPs (Eduljee & Dyke 1996). POP has special physicochemical characteristics that permit them to resist degradation, and traverse bioaccumulate over great distances. POPs can enter freshwater and marine habitats by runoff, atmospheric deposition, effluent emissions, and other methods. POPs have a limited solubility in water, which causes them to bind tightly to the particulate matter in aquatic sediments. This paves the way for many harmful effects that can be seen in human beings and wildlife. People are most likely affected by these substances through the contaminated food and water that they consume or due to exposure to the industries that produce these chemicals. Table 3 presents the concentrations of POPs in different types of water sources. Studies have shown the abnormalities caused in the aquatic life residing in the contaminated water bodies and subsequent effects on their predators. It is necessary to detect POPs, gather information on their sources, brainstorm, and implement methods to reduce their production and effects (Zimmerman *et al.* 2000; Lau *et al.* 2017; Wagner *et al.* 2021).

Several methods are being used to detect the existence of POPs. POPs are difficult to analyse in water samples because in order to detect concentrations at environmental levels, substantial sample volumes would be required owing to their low solubilities. The traditional technique of analysis is using fish tissue; however, biological sampling must be take into account, and additional issues include migration, analyte metabolism, predation, disease, or the possible arrival of a foreign species. The surface-enhanced Raman scattering (SERS) (Sakai *et al.* 2001; Guerrini *et al.* 2008) method uses a molecular assembler and can be used to identify molecules that have been adsorbed onto a metal surface and to determine their most plausible orientation. Due to their incapacity to reach the metal surface, the majority of POPs, with the exception of a few, do not respond to this procedure, which is problematic. Some insecticides seemed to be effective in getting the analyser to come dangerously close to the metal surface. However, pesticides that contain a lot of halogen atoms behave very inertly in SERS. They have no attraction for the metal, and hence, SERS cannot directly detect them. Semipermeable membrane devices (SPMDs) (Abad *et al.* 2000) have proven to be rather efficient, especially compared to traditional chemical analyses. Usually, the tissue of the fish residing in the sample water is analysed, and SPMD has detected low solubility herbicides that cannot be detected commonly in surface water. Fouling factors are used for effective results. Creation of novel sensing components such as MOFs can offer a sizable active surface area as well as the capacity to be stable during target molecule adsorption and desorption. In addition, conceivable is functionalisation. In essence, they are arrangements of inorganic nodes guided by organic linkers. The resulting 3D network has a clear structure, crystallinity, and a sizable amount of porosity. This provides significant sensitivity for detecting guest molecules; in this case, it is the POPs.

There are methods and improvements in the methods mentioned earlier, which are in the process of development. The sources for the POPs that are either intentionally or unintentionally produced are usually from industries, especially the ones that manufacture pesticides. PCBs are POPs that are intentionally produced because they are useful in industrial applications, as heat exchange fluids, power transformers, and sizable capacitors. DDT (trichloroethane) is a controversial pesticide because it is a very effective chemical yet very harmful to the environment. Some manufacturing processes including trash incineration produce POPs unintentionally (Sakai *et al.* 1999; Abad *et al.* 2001). Table 4 summarises the sources of the discussed POPs.

To put a bar on the jeopardising effects of these POPs, numerous measures have been taken to eliminate or reduce emissions of dioxins and other related substances. As mentioned earlier, Stockholm Convention on POPs (2001) has been implemented by many countries that propose banning 21 POPs for commercial usage. If treatment is not carried out properly, it may result in accidental production or release of POPs in the environment. Basel Convention (with effect from 1992) had a set of guidelines that also contained numerous POPs destruction and irreversible transformation methods. Table 5 summarises the reduction methods discussed.

Table 4 | Sources for existing/potential POPs

S. no.	POPs/potential POPs	Region of research	Reference
1	NBFRs, NCFRs, PFASs, PPCPs, CUPs	Arctic region	Muir & Norstrom (1994); Bustnes *et al.* (2010); Ma *et al.* (2011); Rigét *et al.* (2019)
2	PFOA, PFOS	Tap and surface water of several countries	Waggott & Wheatland (1978); Lien *et al.* (2006); Ikehata *et al.* (2008); Bao *et al.* (2012); Meffe & de Bustamante (2014); Han & Currell (2017)
3	Chlordane, DDT, endosulfan, endrin, dieldrin, HCH, PBDEs, PCBs	Rivers	Inam *et al.* (2015); Unyimadu *et al.* (2017); Zhang *et al.* (2018); Sevin *et al.* (2018); Moslen *et al.* (2019); Suami *et al.* (2020); Rex & Chakraborty (2022)
4	OCPs, PAHs	Ologe Lagoon, Lagos Nigeria	Aderinola *et al.* (2018); Yusuf *et al.* (2018); Obanya *et al.* (2019a, (2019b)
5	OCPs, PCBs, PBDEs, PCDDs, PCDFs, PFOS, PFOA	Drinking water sources	Bao *et al.* (2012); Hossain *et al.* (2012); Shakeri *et al.* (2015)
6	PCBs, OCPs, PBDEs, PAHs	South America, Western Atlantic Ocean	Kucklick *et al.* (2011); Luek *et al.* (2017); Barletta *et al.* (2019)
7	PCDDs, PCDFs, PCBs, HCB	Lagoon of Venice	Bettiol *et al.* (2005); Guerzoni *et al.* (2007); Gómez-Gutiérrez *et al.* (2007); Raccanelli *et al.* (2009); Parolini *et al.* (2010)
8	Lindane, p,p'-DDE, p,p'-DDD, endosulfan sulphate, PCBs	Fish farms in Punjab, India	Singh *et al.* (2015); Bedi *et al.* (2018)
9	atrazine, malathion, malaoxon, naphthalene, phenanthrene	Western Bengal Basin, India	Duttagupta (2019); Duttagupta *et al.* (2020a, 2020b)

Note: NBFR, novel brominated flame retardant;. NCFR, novel chlorinated flame retardant; PFAS, polyfluoroalkyl substance; PPCP, pharmaceuticals and personal care product; CUP, current-use pesticide; PFOA, perfluorooctanoic acid; PFOS, perfluorooctanoic sulfonate; DDT, dichloro-diphenyl-trichloroethane; HCH, hexachlorocyclohexane; OCP, organochlorine pesticide; PCB, polychlorinated biphenyl; PBDE, polybrominated diphenyl ether; PAH, polycyclic aromatic hydrocarbon; PCDD/F, polychlorinated-dibenzo-p-dioxins and dibenzofuran; HCB, hexachlorobenzene; p,p′-DDE, dichlorodiphenyldichloroethylene; p,p′-DDD, dichlorodiphenyldichloroethane.

Table 5 | Different methods used to remove POPs along with its operating condition

S. No.	Method	POPs Removed	Operating conditions	Authors
1	Alkali metal reduction	Major-PCBs. In small quantities – dioxins, furans, hexachlorobenzene, and dieldrin	1–4 atm, 100–180 °C	Weber (2007)
2	Base-catalysed decomposition	DDT, HCB, PCBs, PCDDs, and PCDFs	300–350 °C	Rahuman *et al.* (2000); Kubal *et al.* (2004); Weber (2007)
3	Catalytic hydrodechlorination	HCB, PCDDs, PCDFs	1 atm, 180–260 °C, Pd/C catalyst, paraffin oil as reaction solvent,	Ohno (1997); Noma *et al.* (2002, 2003)
4	Gas-phase chemical reduction	PCBs, PCDDs, PCDFs, aldrin, dieldrin, HCBs, PAHs, organochlorine pesticides, DDT	>850 °C	Kummling *et al.* (1997)
5	Hazardous waste incineration	Annex A POPs	1,200–1,600 °C	Sakai *et al.* (1999, 2001); Abad *et al.* (2000, 2001); Everaert & Baeyens (2002); Altarawneh *et al.* (2009)
6	Plasma arc	PCBs	>10,000 °C, 150 kW DC	Zhu & Kang (2014)
7	Nano-adsorbents	PCBs, PFOS, PFOA, DDT	2–9 pH, 10–28 °C	Ismail *et al.* (2018)
8	Electrocoagulation	PAHs, PCDDs, PCDFs	30–50 °C	Pariatamby & Kee (2016)
9	Ionising radiation	Lindane, dieldrin, DDT, heptachlor	0.3–5 MeV, 200 kW	Trojanowicz (2020)
10	Hydrodynamic cavitation	Dicofol	5 atm, 3 pH, 300 °C	Badmus *et al.* (2018)

5.1. Biological methods to remove POP

The use of microorganisms in biodegradation is an environmentally sustainable and cost-effective method for eliminating organic contaminants from soil and water. By cleaning up the environment, the biodegradation process aims to maintain regular biological activities in the surrounding environment. It is a process called biodegradation wherein live microorganisms break down complex chemical molecules into simpler ones. The utilisation of economical and cost-effective inputs yields better outcomes using biodegradation technology, which is highly favoured over conventional approaches. Since biodegradation is a more popular, cost-effective, and environmentally beneficial solution to the issue caused by organic contaminants, it can thus be taken into consideration (Gaur *et al.* 2018). POPs can be removed via microbial decomposition; however, this process is frequently hampered by the low bioavailability of POPs. For soil bioremediation, it is crucial to increase the bioavailability of POPs (Ren *et al.* 2018). Microalgae have demonstrated the ability to remove POPs from the environment through a variety of methods. Among the several methods, biodegradation is one of the best methods that completely eliminate POPs from the environment. As a result, employing microalgae to remove POPs offers a practical substitute for efficiently clean polluted environments and wastewater while also conserving resources (Singh *et al.* 2022).

5.2. Adsorption

The adsorption procedure has shown to be a more successful way to remove POPs and, for the most part, comply with discharge requirements. POPs from aqueous solutions may be efficiently adsorbent by nanomaterials. An adsorptive clearance effectiveness of $>70\%$ was attained for the majority of POPs. Electrostatic contact, hydrophobic interaction, and hydrogen bonding are the main processes for POPS absorption by nano-adsorbents. For around three cycles, nano-adsorbent may maintain an adsorptive removal of $>90\%$ POPs and can be reused for up to 10 cycles. There are difficulties with secure disposal and environmental toxicity of adsorbents (Ighalo *et al.* 2022). Technologies that are both economical and energy efficient for removing POPs from water include adsorptive removal and photocatalytic degradation. Both have garnered significant interest in treating wastewater worldwide. In terms of adsorptive removal and photocatalytic degradation of POPs for water remediation, MOFs – a class of recently created multifunctional porous materials – have demonstrated enormous promise and a bright future (Pi *et al.* 2018).

Adsorption removal of persistent POPs is a simple, practical solution, especially in decentralised systems and locations that are remote, whereas photocatalytic removal of POPs is an excellent, efficient, and durable technique (Ahmad *et al.* 2022). For the very successful elimination of POPs, it is essential to create novel adsorbents and catalysts for photosynthesis with the appropriate structure, adjustable chemistry, and maximal adsorption sites. MOFs are a type of recently developed multifunctional porous substances that have enormous potential for adsorption and photocatalytic destruction of POPs in case of cleaning water (Naghdi *et al.* 2023). Due to their unique chemical and physical features, cyclodextrins are inexpensive and eco-friendly pollution adsorbents (Trojanowicz *et al.* 2020; Titchou *et al.* 2021). Cyclodextrins are also widely reported to be functionalised using a variety of processes, and they are also extremely simple to employ. In addition, a number of derivatives of cyclodextrin are known, and a few of them are offered commercially. By adopting a variety of techniques, such as adsorption, cyclodextrin- and cyclodextrin-functionalised materials might be utilised to remove various contaminants (Wacławek *et al.* 2022).

5.3. Photochemical processes

Photochemical processes (advanced oxidation processes) have a number of benefits, but one of the most advantageous is how good it is at producing extremely reactive oxidising free radicals of OH *in situ* from water. POPs in sewage can be treated successfully using hydrodynamic cavitation technique as well as other cutting-edge oxidation techniques according to investigations (Badmus *et al.* 2018). These contaminants cannot be reduced by conventional wastewater treatment systems. Adsorption removal and photocatalytic breakdown of POPs in water have been found to be energy and cost-effective remedies (Wang *et al.* 2019). For their attempts to clean the wastewater produced across the world, both systems have drawn considerable attention.

The fundamental ideas and fundamental workings of photocatalysts based on titanium dioxide substances, light-assisted Fenton systems, metal oxides, framework materials like MOFs and polyoxometalates, as well as metal-free and hybrid photocatalysts for POPs removal, are described for potential uses in addressing POPs pollution in the surroundings. The crucial issues for the new contaminants are the enhancements of photocatalytic efficiency, particularly the elimination of POP mechanism using traditional and improved process, the design and optimisation of photoreactors, and the incorporation of technological advances. These issues demand extensive study in the near future (Nguyen *et al.* 2020).

5.4. Alkali metal reduction

For the remediation of Askarel converters (>10,000 mg/g of PCBs) and lubricants containing up to 10,000 ppm of PCBs, alkali metal reduction has been employed (Weber 2007). Figure 2 shows the process flow diagram for alkali metal reduction of PCB-contaminated oil. In this process, wastes are treated using dispersed metallic alkali. Chlorine in halogenated non-aqueous waste combines with metallic alkali to form salt and non-halogenated trash (Sun *et al.* 2020).

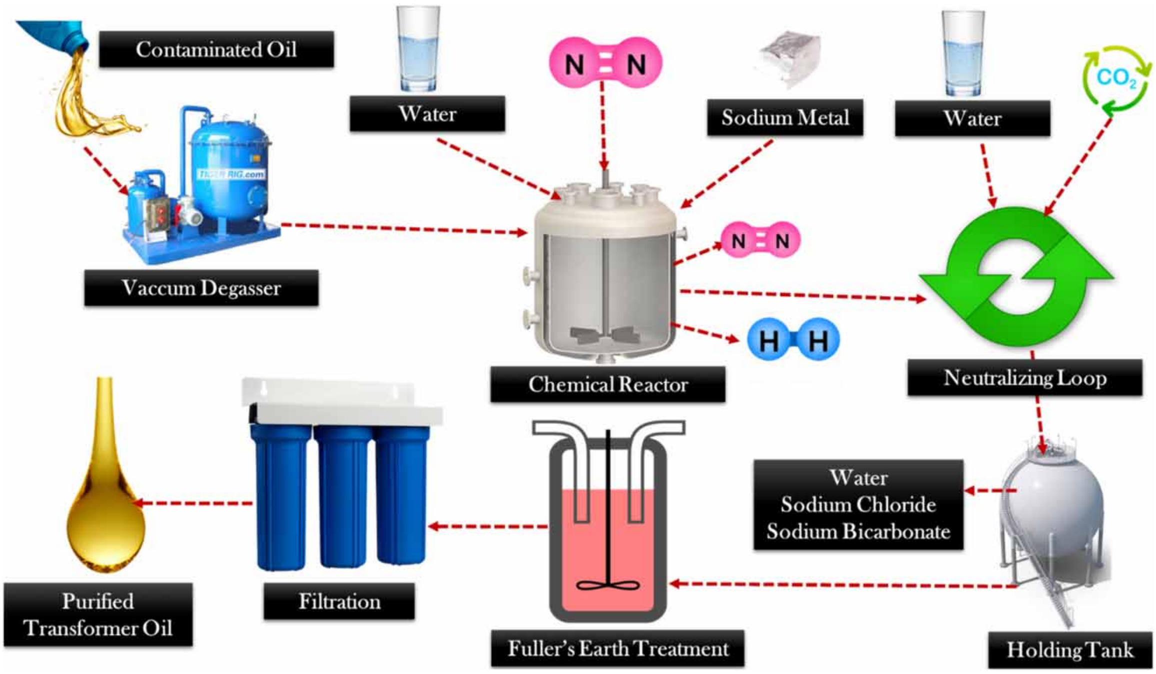


Figure 2 | Process flow diagram of alkali metal reduction of PCB-contaminated oil.

5.5. Base-catalysed decomposition

Base-catalysed decomposition (BCD) has demonstrated efficiency in the treatment of wastes with a PCB level exceeding 30% and high POP concentrations in wastewater (Kubal *et al.* 2004; Weber 2007; Weber *et al.* 2015). Sewage, sediments, liquids, and soil are some of the waste matrices that may be utilised. It has reportedly been demonstrated to erase PCBs from materials made of metal, timber, and paper. Using a reagent consisting of sodium hydroxide, a specialised catalyst, and high-boiling point fuels like type 6 fuel oil, the BCD process, as shown in Figure 3, treats both liquid and solid wastes. The reagent releases highly reactive atomic hydrogen when heated to about 300 °C, which cleaves chemical bonds that give compounds their toxicity. The use of this technology is generally thought to present few risks to one's health and safety (Rahuman *et al.* 2000).

5.6. Catalytic hydrodechlorination

Catalytic hydrodechlorination (CHD) can be used to get rid of POPs such PCBs and dioxins (PCDDs/PCDFs) (Noma *et al.* 2002). Figures 4 and 5 clearly illustrate the chemical reaction of CHD. Utilising hydrogen gas and a palladium-on-carbon (Pd/C) catalyst dissolved in liquid paraffin, waste is handled using this method. Hydrogen and chlorine combine to create non-halogenated trash and hydrogen chloride (HCl) in halogenated waste. PCBs' main by-product is biphenyl. The procedure operates at atmospheric temperature and pressure between 180 and 260 °C (Ohno 1997; Noma *et al.* 2003).

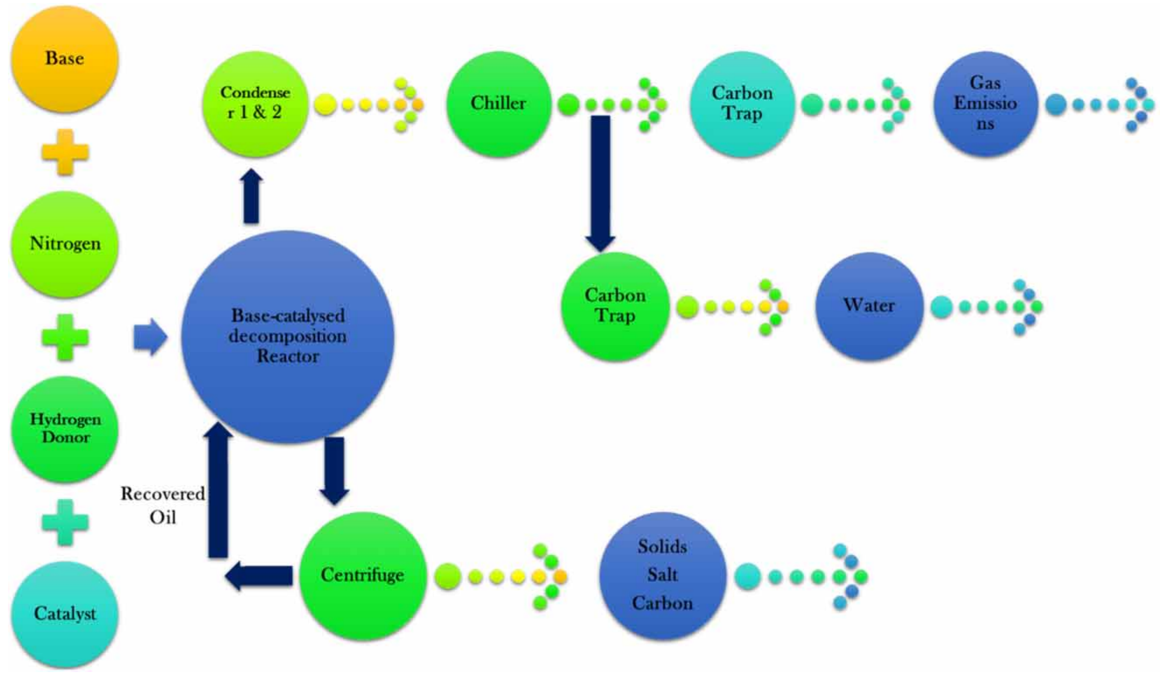


Figure 3 | Process diagram of base-catalysed decomposition.

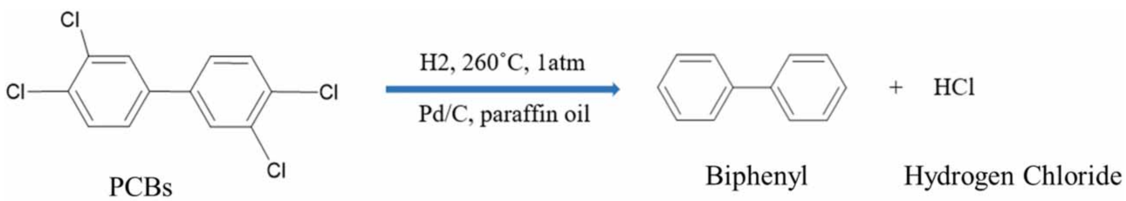


Figure 4 | Chemical reaction of catalytic hydrodechlorination.

5.7. Gas-phase chemical reduction

The gas-phase chemical reduction (GPCR) method, which uses hydrogen and steam at temperatures that is at least 850 °C, decreases organic molecules (which serves as a heat transfer agent and another source of hydrogen). As a result of the breakdown of organic compounds, methane, hydrogen chloride (if the sewage is chlorinated), and trace amounts of low-molecular-weight compounds are produced (benzene and ethylene). The hydrochloric acid is balanced during the first cooling of the gas mixture by the injection of soda ash, or it can be withdrawn in acid form for reuse if necessary. The reactor's 'product gas' is compressed and studied after being cooled and scrubbed. The front-end system, reactor, and gas cleaning and compression system are the three primary components of the GPCR technology as shown in Figure 6 (Kummling *et al.* 1997).

5.8. Hazardous waste incineration

POPs, including such PCB lubricants from dismantled transformers and chlorinated pesticides, may be included in in a hazardous waste mixture for burning in a specialised waste incinerator. It might include pollutants contaminated with POPs, such as commercial waste and activated carbon screens used to clean the exhaust gases in burning facilities (Abad *et al.* 2000; Abad *et al.* 2001). To get rid of these POPs, incinerator's processing parameters are modified. Nevertheless, once the burning gases are cooled down, more POPs are produced, chiefly PCDD/Fs and PCBs (Sakai *et al.* 1999, 2001). These POPs are found in the incineration residues, especially in the fly and furnace ashes and in the gas cleaning residues, in addition to being emitted with the flue gases at the stack (Everaert & Baeyens 2002; Altarawneh *et al.* 2009).

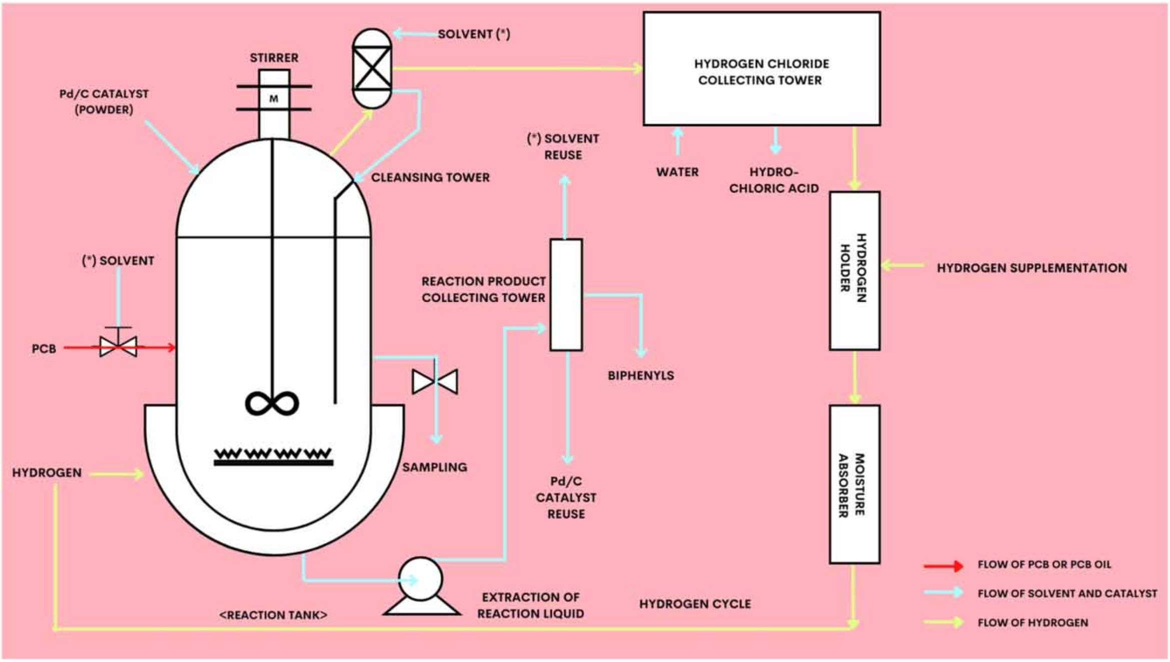


Figure 5 | Process diagram of catalytic hydrodechlorination reaction.

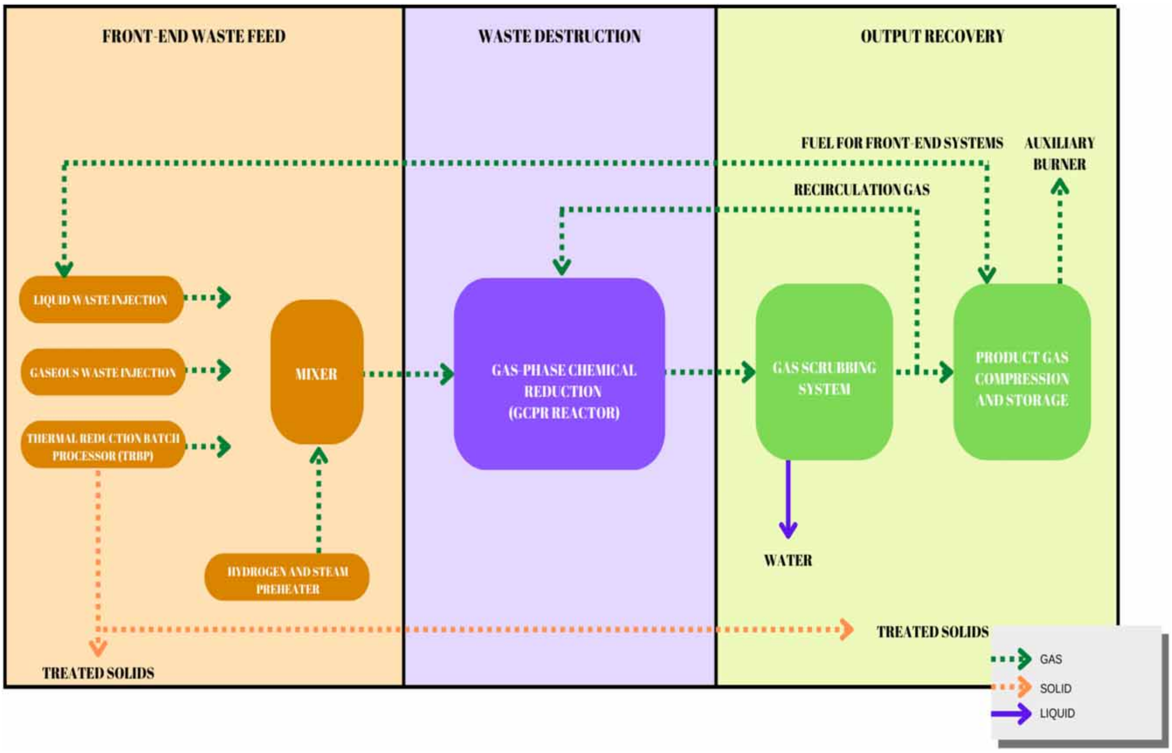


Figure 6 | Block diagram of gas-phase chemical reduction process.

5.9. Plasma arc

An ionised gas-like material called plasma is made up of electron-deprived and electron-positron atoms. Numerous properties of plasma, including electric conversion efficiency, quick response, high thermal capacity, and high energy, offer distinct advantages and promising prospects for effective disposal of POPs wastes (Girolkar *et al.* 2021).

Using a non-combustion process, plasma arc technology can be applied to manage organic fluoride in phenyl chlorosilane residue, industrial waste, and HFC23 (Zhu & Kang 2014).

5.10. Other miscellaneous studies

Antibacterial bimetallic Ag-Cu nanoparticles were made via green synthesis for catalytic reduction of POPs (Ismail *et al.* 2018). It was concluded that Ag-Cu/T.P. is extremely suitable for the catalytic reduction of organic molecules due to its abundance, affordability, and effective catalytic degradation. Natural coagulants like Xantham and Guar gum are effective in treating POPs, and it is a well-recommended option due to their various salient features, including their abundance, cheap maintenance, and biodegradable biopolymer properties (Pariatamby & Kee 2016). POPs are removed from sewage and sources of water using ionising radiation (Trojanowicz 2020).

6. CIRCULAR ECONOMY IN POP REMOVAL

The wastewater treatment industry is one area where the circular economy may be used. Consideration of wastewater recovery and reuse, for instance, appears to be a great way to boost water supplies while lowering environmental effects. Wastewater can be sufficiently treated by the technique to be safe for human use. Agricultural, industrial, urban, environmental, or recreational uses are the most popular uses of recovered wastewater because this concept is still unpopular with most people and is referred to as the 'yuck factor'. Nevertheless, there are many opportunities to implement the circular economy if we consider not just the resource worth of water but also the materials present in these effluents. As an illustration, it is commonly recognised that wastewater may be used to recover energy and nutrients. Other potential uses include the recovery of metals, organic and inorganic chemicals, biomolecules, and more. However, there are also ways to implement a circular economy in the water sector, such as by making money off of sewage sludge (Guerra-Rodríguez *et al.* 2020). Therefore, while both POP regulation and climate action, which heavily emphasises plastic recycling, are necessary for a circular economy, they are incompatible. The development of recycling methods, which allow for the separation and safe destruction of such materials, is one way to address this disparity (Wagner & Schlummer 2020).

7. CONCLUSION

This review article aims to give the readers an insight into the growing concern about the effects of POPs in water bodies. It throws light on the potential environmental and public health risks. Despite tighter controls at the national and international levels, the general public is nevertheless exposed to POPs at levels that might have long-term consequences on their health. POPs are present in extremely minute amounts and cannot be properly removed by traditional methods. Based on the contaminants' physicochemical properties, a sophisticated treatment must be selected. The unique features of nanomaterials, which are excellent for many environmental applications, have transformed the field of wastewater treatment. The research in the coming years will hopefully be able to change the situation, but the urge to reduce the production of these chemicals will always remain.

8. FUTURE PROSPECTS

Some strategies could be implemented to reduce POPs or find suitable and safer alternatives to these contaminants. The strategies include functional substitution, chemical management, and chemical safety analysis. It has been concluded that studies done on POPs should not only focus on their risk factors but also on their function. These approaches pave the way for decision-making and can produce safer chemicals in the long run. The chemical function is an important criterion that might help synthesize safer chemicals. Chemists design chemicals to have specific properties that have specific functions. This enables chemists to reduce the toxicity of chemicals. One can consider the end-use function as an alternative, as it involves degreasing and other methods that achieve the same.

POPs use can be reduced by identifying alternatives to replace them that are way safer for global health and the environment. The functional substitution approach provides an easier and more feasible method for finding safe alternatives, which leaves us with many options that replace the chemicals with higher toxic content with safe alternative. With expanding research in nanotechnology, nanomaterials, based on their nature, can prove to be a promising remedy for removing POPs with high efficiency. Climate change has an effect on POP exposure concerns and transport processes in a variety of media, including air–soil gas exchange, emissions from melting glaciers, air–water gas exchange, and bioaccumulation in food web.

The augmentation of POP re-emission from soil, water, and glaciers, as well as the increase in POP concentrations in the world's polar areas, are only a few of the many effects of climate change. Therefore, it is urgent to increase the development and investigation of greener, more sustainable alternatives for POP mitigation. Adopting phytoremediation, a widely utilised integrated approach that uses bacteria and plants to break down toxins, could remove POPs without harming the environment. However, the primary focus is on maximum eradication of POPs usage rather than removal of POPs.

AUTHOR CONTRIBUTION

Aindrila Mandal, C. S. Poorva, S. Lohita: investigation, methodology, and writing – review and editing. P. Senthil Kumar: conceptualisation, validation, and supervision. B. Senthil Rathi, Gayathri Rangasamy: conceptualisation, resources, and formal analysis.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abad, E., Adrados, M. A., Caixach, J., Fabrellas, B. & Rivera, J. 2000 Dioxin mass balance in a municipal waste incinerator. *Chemosphere* **40**(9–11), 1143–1147.

Abad, E., Adrados, M. A., Caixach, J. & Rivera, J. 2001 Dioxin abatement strategies and mass balance at a municipal waste management plant. *Environmental Science & Technology* **36**(1), 92–99.

Aderinola, O. J., Mekuleyi, G. O. & Whenu, O. O. 2018 Total and polyaromatic hydrocarbons in water, sediment, fin and shellfishes from Badagry Creek and Ologe Lagoon, Lagos, Nigeria. *Journal of Applied Sciences and Environmental Management* **22**(5), 675–680.

Adithya, S., Jayaraman, R. S., Krishnan, A., Malolan, R., Gopinath, K. P., Arun, J., Kim, W. & Govarthanan, M. 2021 A critical review on the formation, fate and degradation of the persistent organic pollutant hexachlorocyclohexane in water systems and waste streams. *Chemosphere* **271**, 129866.

Ahmad, A., Priyadarshini, M., Yadav, S., Ghangrekar, M. M. & Surampalli, R. Y. 2022 The potential of biochar-based catalysts in advanced treatment technologies for efficacious removal of persistent organic pollutants from wastewater: A review. *Chemical Engineering Research and Design* **187**, 470–496.

Alharbi, O. M., Khattab, R. A. & Ali, I. 2018 Health and environmental effects of persistent organic pollutants. *Journal of Molecular Liquids* **263**, 442–453.

Ali, I., Wani, W. A. & Saleem, K. 2011 Cancer scenario in India with future perspectives. *Cancer Therapy* **8**, 56.

Altarawneh, M., Dlugogorski, B. Z., Kennedy, E. M. & Mackie, J. C. 2009 Mechanisms for formation, chlorination, dechlorination and destruction of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs). *Progress in Energy and Combustion Science* **35**(3), 245–274.

Badmus, K. O., Tijani, J. O., Massima, E. & Petrik, L. 2018 Treatment of persistent organic pollutants in wastewater using hydrodynamic cavitation in synergy with advanced oxidation process. *Environmental Science and Pollution Research International* **25**(8), 7299–7314.

Bao, L. J., Maruya, K. A., Snyder, S. A. & Zeng, E. Y. 2012 China's water pollution by persistent organic pollutants. *Environmental Pollution* **163**, 100–108.

Barletta, M., Lima, A. R. & Costa, M. F. 2019 Distribution, sources and consequences of nutrients, persistent organic pollutants, metals and microplastics in South American estuaries. *Science of the Total Environment* **651**, 1199–1218.

Bedi, J. S., Singh, V., Gupta, A., Gill, J. P. S. & Aulakh, R. S. 2018 Persistent organic pollutants (POPs) in fresh water farm fish species from Punjab (India) and evaluation of their dietary intake for human risk assessment. *Human and Ecological Risk Assessment: An International Journal* **24**(6), 1659–1672.

Bettiol, C., Collavini, F., Guerzoni, S., Molinaroli, E., Rossini, P., Zaggia, L. & Zonta, R. 2005 Atmospheric and riverine inputs of metals, nutrients and persistent organic pollutants into the lagoon of Venice. *Hydrobiologia* **550**(1), 151–165.

Boulkhessaim, S., Gacem, A., Khan, S. H., Amari, A., Yadav, V. K., Harharah, H. N., Elkhaleefa, A. M., Yadav, K. K., Rather, S. U., Ahn, H. J. & Jeon, B. H. 2022 Emerging trends in the remediation of persistent organic pollutants using nanomaterials and related processes: A review. *Nanomaterials* **12**(13), 2148.

Breivik, K., Alcock, R., Li, Y.-F., Bailey, R. E., Fiedler, H. & Pacyna, J. M. 2004 Primary sources of selected POPs: Regional and global scale emission inventories. *Environmental Pollution* **128**(1–2), 3–16.

Buser, H. R., Müller, M. D., Buerge, I. J. & Poiger, T. 2009 Composition of aldrin, dieldrin, and photodieldrin enantiomers in technical and environmental samples. *Journal of Agricultural and Food Chemistry* **57**(16), 7445–7452.

Bustnes, J. O., Gabrielsen, G. W. & Verreault, J. 2010 Climate variability and temporal trends of persistent organic pollutants in the Arctic: A study of glaucous gulls. *Environmental Science & Technology* **44**(8), 3155–3161.

Carpenter, D. O. 2008 Environmental contaminants as risk factors for developing diabetes. *Reviews on Environmental Health* **23**(1), 59–74.

Chaput, J. P., Doucet, E. & Tremblay, A. 2012 Obesity: A disease or a biological adaptation? An update. *Obesity Reviews* **13**(8), 681–691.

Chen, Y., Zhi, D., Zhou, Y., Huang, A., Wu, S., Yao, B., Tang, Y. & Sun, C. 2021 Electrokinetic techniques, their enhancement techniques and composite techniques with other processes for persistent organic pollutants remediation in soil: A review. *Journal of Industrial and Engineering Chemistry* **97**, 163–172.

Dahiya, V., Anand, B. G., Kar, K. & Pal, S. 2021 Analyzing organophosphate pesticide-serum albumin binding interaction: A combined STD NMR and molecular docking study. *Journal of Biomolecular Structure and Dynamics* **39**(5), 1865–1878.

Devi, N. L. 2020 Persistent organic pollutants (POPs): Environmental risks, toxicological effects, and bioremediation for environmental safety and challenges for future research. In: Saxena, G. & Bharagava, R. (eds). *Bioremediation of Industrial Waste for Environmental Safety: Volume I: Industrial Waste and Its Management* (Saxena, G. & Bharagava, R., eds)., Springer, Singapore, pp. 53–76. https://doi.org/10.1007/978-981-13-1891-7_4

Dichiarante, V., Cavallo, G. & Metrangolo, P. 2021 Endocrine-disrupting pollutants properties affecting their bioactivity, remediation, and detection. *Current Opinion in Green and Sustainable Chemistry* **30**, 100485.

Duttagupta, S. 2019 *Occurrence, Fate and Transport of Persistent Organic Pollutants in Natural Water and Sediment of Western Bengal Basin*. *Doctoral dissertation*, IIT Kharagpur.

Duttagupta, S., Mukherjee, A., Das, K., Dutta, A., Bhattacharya, A. & Bhattacharya, J. 2020a Groundwater vulnerability to pesticide pollution assessment in the alluvial aquifer of Western Bengal basin, India using overlay and index method. *Geochemistry* **80**(4), 125601.

Duttagupta, S., Mukherjee, A., Bhattacharya, A. & Bhattacharya, J. 2020b Wide exposure of persistent organic pollutants (PoPs) in natural waters and sediments of the densely populated Western Bengal basin, India. *Science of the Total Environment* **717**, 137187.

Eduljee, G. H. & Dyke, P. 1996 An updated inventory of potential PCDD and PCDF emission sources in the UK. *Science of the Total Environment* **177**(1–3), 303–321.

El-Shahawi, M. S., Hamza, A., Bashammakh, A. S. & Al-Saggaf, W. T. 2010 An overview on the accumulation, distribution, transformations, toxicity and analytical methods for the monitoring of persistent organic pollutants. *Talanta* **80**(5), 1587–1597.

Everaert, K. & Baeyens, J. 2002 The formation and emission of dioxins in large scale thermal processes. *Chemosphere* **46**(3), 439–448.

Farha, O. K., Eryazici, I., Jeong, N. C., Hauser, B. G., Wilmer, C. E., Sarjeant, A. A., Snurr, R. Q., Nguyen, S. T., Yazaydın, A. Ö. & Hupp, J. T. 2012 Metal–organic framework materials with ultrahigh surface areas: Is the sky the limit? *Journal of the American Chemical Society* **134**(36), 15016–15021.

Fenstad, A. A., Jenssen, B. M., Gabrielsen, K. M., Öst, M., Jaatinen, K., Bustnes, J. O., Hanssen, S. A., Moe, B., Herzke, D. & Krøkje, Å. 2016 Persistent organic pollutant levels and the importance of source proximity in Baltic and Svalbard breeding common eiders. *Environmental Toxicology and Chemistry* **35**(6), 1526–1533.

Fernandez, A., Singh, A. & Jaffé, R. 2007 A literature review on trace metals and organic compounds of anthropogenic origin in the Wider Caribbean Region. *Marine Pollution Bulletin* **54**(11), 1681–1691.

Fitzgerald, L. & Wikoff, D. S. 2014 Persistent organic pollutants. *Encyclopedia of Toxicology,* 3rd edn, vol. 3. Elsevier, Inc., Academic Press, pp. 820–825.

Gaur, N., Narasimhulu, K. & PydiSetty, Y. 2018 Recent advances in the bio-remediation of persistent organic pollutants and its effect on environment. *Journal of Cleaner Production* **198**, 1602–1631.

Girolkar, S., Thawale, P. & Juwarkar, A. 2021 Bacteria-assisted phytoremediation of heavy metals and organic pollutants: Challenges and future prospects. Sneha Girolkar, Prashant Thawale, Asha Juwarkar, Chapter 12 - Bacteria-assisted phytoremediation of heavy metals and organic pollutants: challenges and future prospects, In: Kumar, V., Gaurav Saxena, G. & Maulin P. Shah, M. P. (eds Bioremediation for Environmental Sustainability, Elsevier, pp. 247–267. ISBN 9780128203187, https://doi.org/10.1016/B978-0-12-820318-7.00012-5.

Gómez-Gutiérrez, A., Garnacho, E., Bayona, J. M. & Albaigés, J. 2007 Assessment of the Mediterranean sediments contamination by persistent organic pollutants. *Environmental Pollution* **148**(2), 396–408.

Gonsioroski, A., Mourikes, V. E. & Flaws, J. A. 2020 Endocrine disruptors in water and their effects on the reproductive system. *International Journal of Molecular Sciences* **21**(6), 1929.

Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D. N. & Rodríguez-Chueca, J. 2020 Towards the implementation of circular economy in the wastewater sector: Challenges and opportunities. *Water* **12**(5), 1431.

Guerrini, L., Aliaga, A. E., Cárcamo, J., Gómez-Jeria, J. S., Sanchez-Cortes, S., Campos-Vallette, M. M. & García-Ramos, J. V. 2008 Functionalization of Ag nanoparticles with the bis-acridinium lucigenin as a chemical assembler in the detection of persistent organic pollutants by surface-enhanced Raman scattering. *Analytica Chimica Acta* **624**(2), 286–293.

Guerzoni, S., Rossini, P., Sarretta, A., Raccanelli, S., Ferrari, G. & Molinaroli, E. 2007 POPs in the Lagoon of Venice: Budgets and pathways. *Chemosphere* **67**(9), 1776–1785.
Han, D. & Currell, M. J. 2017 Persistent organic pollutants in China's surface water systems. *Science of the Total Environment* **580**, 602–625.
Hectors, T. L. M., Vanparys, C., Van Der Ven, K., Martens, G. A., Jorens, P. G., Van Gaal, L. F., Covaci, A., De Coen, W. & Blust, R. 2011 Environmental pollutants and type 2 diabetes: A review of mechanisms that can disrupt beta cell function. *Diabetologia* **54**(6), 1273–1290.
Hossain, M. M., Islam, K. N. & Rahman, I. M. 2012 An overview of the persistent organic pollutants in the freshwater system. *Ecological Water Quality-Water Treatment and Reuse* **24**, 455–470.
Hu, J., Zhu, T. & Li, Q. 2007 Organochlorine pesticides in China. *Developments in Environmental Science* **7**, 159–211.
Ighalo, J. O., Yap, P. S., Iwuozor, K. O., Aniagor, C. O., Liu, T., Dulta, K., Iwuchukwu, F. U. & Rangabhashiyam, S. 2022 Adsorption of persistent organic pollutants (POPs) from the aqueous environment by nano-adsorbents: A review. *Environmental Research* **212**, 113123.
Ikehata, K., Gamal El-Din, M. & Snyder, S. A. 2008 Ozonation and advanced oxidation treatment of emerging organic pollutants in water and wastewater. *Ozone: Science and Engineering* **30**(1), 21–26.
Inam, E., Offiong, N.-A., Kang, S., Yang, P. & Essien, J. 2015 Assessment of the occurrence and risks of emerging organic pollutants (EOPs) in Ikpa River Basin Freshwater Ecosystem, Niger Delta–Nigeria. *Bulletin of Environmental Contamination and Toxicology* **95**(5), 624–631.
Islam, R., Kumar, S., Karmoker, J., Kamruzzaman, M., Rahman, M. A., Biswas, N., Tran, T. K. A. & Rahman, M. M. 2018 Bioaccumulation and adverse effects of persistent organic pollutants (POPs) on ecosystems and human exposure: A review study on Bangladesh perspectives. *Environmental Technology & Innovation* **12**, 115–131.
Ismail, M., Khan, M. I., Khan, S. A., Qayum, M., Khan, M. A., Anwar, Y., Akhtar, K., Asiri, A. M. & Khan, S. B. 2018 Green synthesis of antibacterial bimetallic Ag–Cu nanoparticles for catalytic reduction of persistent organic pollutants. *Journal of Materials Science: Materials in Electronics* **29**(24), 20840–20855.
Jacobson, J. L., Jacobson, S. W. & Humphrey, H. E. 1990a Effects of exposure to PCBs and related compounds on growth and activity in children. *Neurotoxicology and Teratology* **12**(4), 319–326.
Jacobson, J. L., Jacobson, S. W. & Humphrey, H. E. 1990b Effects of in utero exposure to polychlorinated biphenyls and related contaminants on cognitive functioning in young children. *The Journal of Pediatrics* **116**(1), 38–45.
Johansen, S., Poste, A., Allan, I., Evenset, A. & Carlsson, P. 2021 Terrestrial inputs govern spatial distribution of polychlorinated biphenyls (PCBs) and hexachlorobenzene (HCB) in an Arctic fjord system (Isfjorden, Svalbard). *Environmental Pollution* **281**, 116963.
Kallenborn, R., Breivik, K., Eckhardt, S., Lunder, C. R., Manø, S., Schlabach, M. & Stohl, A. 2013 Long-term monitoring of persistent organic pollutants (POPs) at the Norwegian Troll station in Dronning Maud Land, Antarctica. *Atmospheric Chemistry and Physics* **13**(14), 6983–6992.
Karthigadevi, G., Manikandan, S., Karmegam, N., Subbaiya, R., Chozhavendhan, S., Ravindran, B., Chang, S. W. & Awasthi, M. K. 2021 Chemico-nanotreatment methods for the removal of persistent organic pollutants and xenobiotics in water – A review. *Bioresource Technology* **324**, 124678.
Kodavanti, P. R. S., Royland, J. E. & Rao, K. S. 2014 Toxicology of persistent organic pollutants. *Reference Module in Biomedical Sciences*, Elsevier. https://doi.org/10.1016/B978-0-12-801238-3.00211-7.
Kubal, M., Fairweather, J., Crain, P. & Kuraš, M. 2004 Treatment of solid waste polluted by polychlorinated contaminants (pilot-scale demonstration). *WIT Transactions on Ecology and the Environment* **78**, 13–23.
Kucklick, J., Schwacke, L., Wells, R., Hohn, A., Guichard, A., Yordy, J., Hansen, L., Zolman, E., Wilson, R., Litz, J. & Nowacek, D. 2011 Bottlenose dolphins as indicators of persistent organic pollutants in the western North Atlantic Ocean and northern Gulf of Mexico. *Environmental Science & Technology* **45**(10), 4270–4277.
Kummling, K., Festarini, L., Woodland, S., Kornelsen, P. & Hallett, D. 1997 An evaluation of levels of chlorinated aromatic compounds in Eco Logic process stack outputs. *Organohalogen Cpds* **32**, 66–71.
Lau, G., Walter, K., Kass, P. & Puschner, B. 2017 Comparison of polybrominated diphenyl ethers (PBDEs) and polychlorinated biphenyls (PCBs) in the serum of hypothyroxinemic and euthyroid dogs. *PeerJ* **5**, e3780.
Lee, C. W., Lemieux, P. M., Gullett, B. K., Ryan, J. V. & Kilgroe, J. D. 1998 Research on emissions and mitigation of POP's from combustion sources. In: Studies in Environmental Science 72, *Air Pollution in the 21st Century – Priority Issues and Policy*, (Schneider, T., ed.), Elsevier Science BV, Amsterdam, Netherlands, pp. 361–378.
Lien, N. P. H., Fujii, S., Tanaka, S., Nozoe, M., Wirojanagud, W., Anton, A. & Lindstrom, G. 2006 Perfluorinated substances in tap water of Japan and several countries and their relationship to surface water contamination. *Environmental Engineering Research* **43**, 611–618.
Liu, Z., Zheng, G. & Liu, Z. 2020 Organochlorine pesticides in surface water of Jiuxi Valley, China: Distribution, source analysis, and risk evaluation. *Journal of Chemistry* **2020**, 1–8.
Liu, Z., Ren, X., Duan, X., Sarmah, A. K. & Zhao, X. 2023 Remediation of environmentally persistent organic pollutants (POPs) by persulfates oxidation system (PS): A review. *Science of the Total Environment* **863**, 160818.
Ljunggren, S. A., Helmfrid, I., Salihovic, S., van Bavel, B., Wingren, G., Lindahl, M. & Karlsson, H. 2014 Persistent organic pollutants distribution in lipoprotein fractions in relation to cardiovascular disease and cancer. *Environment International* **65**, 93–99.

Luek, J. L., Dickhut, R. M., Cochran, M. A., Falconer, R. L. & Kylin, H. 2017 Persistent organic pollutants in the Atlantic and southern oceans and oceanic atmosphere. *Science of the Total Environment* **583**, 64–71.
Ma, J., Hung, H., Tian, C. & Kallenborn, R. 2011 Revolatilization of persistent organic pollutants in the Arctic induced by climate change. *Nature Climate Change* **1**(5), 255–260.
Marshall, L., Weir, E., Abelsohn, A. & Sanborn, M. D. 2002 Identifying and managing adverse environmental health effects: 1. Taking an exposure history. *Cmaj* **166**(8), 1049–1055.
Meffe, R. & de Bustamante, I. 2014 Emerging organic contaminants in surface water and groundwater: A first overview of the situation in Italy. *Science of the Total Environment* **481**, 280–295.
Mishra, A., Kumari, M., Kumar, R., Iqbal, K. & Thakur, I. S. 2022 Persistent organic pollutants in the environment: Risk assessment, hazards, and mitigation strategies. *Bioresource Technology Reports* **19**, 101143.
Moslen, M., Ekweozor, I. K. E., Minimah, I. & Ebere, N. 2019 Variation of persistent organic pollutants (pops) in surface water, sediment, and fish from a tidal creek in the Niger Delta Nigeria. *Nigerian Journal of Oil and Gas Technology* **3**(1), 229–239.
Muir, D. C. & Norstrom, R. J. 1994 Persistent organic contaminants in Arctic marine and freshwater ecosystems. *Arctic Research of the United States* **8**, 136–146.
Myre, M. & Imbeault, P. 2014 Persistent organic pollutants meet adipose tissue hypoxia: Does cross-talk contribute to inflammation during obesity? *Obesity Reviews* **15**(1), 19–28.
Naghdi, S., Shahrestani, M. M., Zendehbad, M., Djahaniani, H., Kazemian, H. & Eder, D. 2023 Recent advances in application of metal-organic frameworks (MOFs) as adsorbent and catalyst in removal of persistent organic pollutants (POPs). *Journal of Hazardous Materials* **442**, 130127.
Nguyen, V. H., Smith, S. M., Wantala, K. & Kajitvichyanukul, P. 2020 Photocatalytic remediation of persistent organic pollutants (POPs): A review. *Arabian Journal of Chemistry* **13**(11), 8309–8337.
Nizzetto, L., Macleod, M., Borgå, K., Cabrerizo, A., Dachs, J., Guardo, A. D., Ghirardello, D., Hansen, K. M., Jarvis, A., Lindroth, A. & Ludwig, B. 2010 *Past, Present, and Future Controls on Levels of Persistent Organic Pollutants in the Global Environment* 44, 6526–6531.
Noma, Y., Muramatu, T., Nishizawa, K., Ohno, M. & Sakai, S. I. 2002 Dechlorination pathways of PCBS by photochemical reaction and catalytic hydro-dechlorination. *Organohalogen Compounds* **56**, 413–416.
Noma, Y., Ohno, M. & Sakai, S. I. 2003 Pathways for the degradation of PCBs by palladium-catalyzed dechlorination. *Fresenius Environmental Bulletin* **12**(3), 302–308.
Nowak, K., Jabłońska, E. & Ratajczak-Wrona, W. 2019 Immunomodulatory effects of synthetic endocrine disrupting chemicals on the development and functions of human immune cells. *Environment International* **125**, 350–364.
Nyaundi, J. K., Omasaki, S. K., Babu, J. M., Mwirigi, N. M., Omondi, R., Mwayulj, G. A. & Bassa, S. 2023 Dissipation of environmental DDT and its metabolites in selected rivers of south-western Kenya. *African Journal of Aquatic Science* **48**(2), 115–122.
Obanya, H. E., Ntor, C., Okoroafor, C. U. & Nwanze, R. 2019a Occurrence of a polychlorinated biphenyl (PCB) congener in surface water, sediments and blackchin tilapia (*Sarotherodon melanotheron*) from Ologe Lagoon, Nigeria. *Journal of Applied Sciences and Environmental Management* **23**(10), 1805–1811.
Obanya, H. E., Omoarukhe, A., Amaeze, N. H. & Okoroafor, C. U. 2019b Polycyclic aromatic hydrocarbons in Ologe lagoon and effects of Benzo [b] fluoranthene in African catfish. *Journal of Health and Pollution* **9**(22), 190605.
Odabasi, M., Dumanoglu, Y., Kara, M., Altiok, H., Elbir, T. & Bayram, A. 2017 Polychlorinated naphthalene (PCN) emissions from scrap processing steel plants with electric-arc furnaces. *Science of the Total Environment* **574**, 1305–1312.
Oginawati, K., Susetyo, S. H., Rahmawati, S. I., Kurniawan, S. B. & Abdullah, S. R. S. 2021 Distribution of organochlorine pesticide pollution in water, sediment, mollusk, and fish at Saguling Dam, West Java, Indonesia. *Toxicological Research* **38**(2), 149–157.
Ohno, M. 1997 Complete destruction of PCB by using a catalytic hydrogenation-dechlorination reaction and t-BuOK method in a bench scale plant. *Organohalogen Compounds* **31**, 405–409.
Pang, S., Yang, T. & He, L. 2016 Review of surface enhanced Raman spectroscopic (SERS) detection of synthetic chemical pesticides. *TrAC Trends in Analytical Chemistry* **85**, 73–82.
Pang, S., Lin, Z., Li, J., Zhang, Y., Mishra, S., Bhatt, P. & Chen, S. 2022 Microbial degradation of aldrin and dieldrin: Mechanisms and Biochemical Pathways. *Frontiers in Microbiology* **13**, 713375.
Panis, C., Candiotto, L. Z. P., Gaboardi, S. C., Gurzenda, S., Cruz, J., Castro, M. & Lemos, B. 2022 Widespread pesticide contamination of drinking water and impact on cancer risk in Brazil. *Environment International* **165**, 107321.
Pariatamby, A. & Kee, Y. L. 2016 Persistent organic pollutants management and remediation. *Procedia Environmental Sciences* **31**, 842–848.
Parolini, M., Binelli, A., Matozzo, V. & Marin, M. G. 2010 Persistent organic pollutants in sediments from the Lagoon of Venice – A possible hazard for sediment-dwelling organisms. *Journal of Soils and Sediments* **10**(7), 1362–1379.
Parra-Arroyo, L., González-González, R. B., Castillo-Zacarías, C., Melchor Martínez, E. M., Sosa-Hernández, J. E., Bilal, M., Iqbal, H. M. N., Barceló, D. & Parra-Saldívar, R. 2022 Highly hazardous pesticides and related pollutants: Toxicological, regulatory, and analytical aspects. *Science of the Total Environment* **807**, 151879.
Pawlak, F., Kozioł, K., Ruman, M. & Polkowska, Ż. 2019 Persistent organic pollutants (POPs) as an indicator of surface water quality in the vicinity of the Polish Polar Station, Horsund. *Monatshefte für Chemie-Chemical Monthly* **150**, 1573–1578.

Peng, S., Kong, D., Li, L., Zou, C., Chen, F., Li, M., Cao, T., Yu, C., Song, J. & Jia, W. 2020 Distribution and sources of DDT and its metabolites in porewater and sediment from a typical tropical bay in the South China Sea. *Environmental Pollution* **267**, 115492.

Pereira-Fernandes, A., Dirinck, E., Dirtu, A. C., Malarvannan, G., Covaci, A., Van Gaal, L., Vanparys, C., Jorens, P. G. & Blust, R. 2014 Expression of obesity markers and persistent organic pollutants levels in adipose tissue of obese patients: Reinforcing the obesogen hypothesis? *PLoS One* **9**(1), e84816.

Pi, Y., Li, X., Xia, Q., Wu, J., Li, Y., Xiao, J. & Li, Z. 2018 Adsorptive and photocatalytic removal of persistent organic pollutants (POPs) in water by metal-organic frameworks (MOFs). *Chemical Engineering Journal* **337**, 351–371.

Predieri, B., Bruzzi, P., Bigi, E., Ciancia, S., Madeo, S. F., Lucaccioni, L. & Iughetti, L. 2020 Endocrine disrupting chemicals and type 1 diabetes. *International Journal of Molecular Sciences* **21**(8), 2937.

Qiao, J. & Xiong, Y. 2021 Electrochemical oxidation technology: A review of its application in high-efficiency treatment of wastewater containing persistent organic pollutants. *Journal of Water Process Engineering* **44**, 102308.

Raccanelli, S., Libralato, S. & Tundo, P. 2009 Fate of persistent organic pollutants in the Venice lagoon: From the environment to human beings through biological exploitation? In: Bahadir, A. M. & Duca, G. (eds). *The Role of Ecological Chemistry in Pollution Research and Sustainable Development*. Springer, Dordrecht, pp. 15–25.

Rahuman, M. S. M. M., Pistone, L., Trifirò, F. & Miertus, S. 2000 Destruction technologies for polychlorinated biphenyls (PCBs). In *Proceedings of Expert Group Meetings on POPs and Pesticides Contamination*, Vol. 16(6), pp. 405–423.

Rashed, M. N. & Summers, J. K. 2022 *Persistent Organic Pollutants (POPs): Monitoring, Impact and Treatment*. InNageeb Rashed, M. (ed.), Environmental Sciences. IntechOpen. doi: 10.5772/intechopen.95151.

Ren, X., Zeng, G., Tang, L., Wang, J., Wan, J., Liu, Y., Yu, J., Yi, H., Ye, S. & Deng, R. 2018 Sorption, transport and biodegradation–An insight into bioavailability of persistent organic pollutants in soil. *Science of the Total Environment* **610**, 1154–1163.

Rex, K. R. & Chakraborty, P. 2022 Legacy and new chlorinated persistent organic pollutants in the rivers of south India: Occurrences, sources, variations before and after the outbreak of the COVID-19 pandemic. *Journal of Hazardous Materials* **437**, 129262.

Rigét, F., Bignert, A., Braune, B., Dam, M., Dietz, R., Evans, M., Green, N., Gunnlaugsdóttir, H., Hoydal, K. S., Kucklick, J., Letcher, R., Muir, D., Schuur, S., Sonne, C., Stern, G., Tomy, G., Vorkamp, K. & Wilson, S. 2019 Temporal trends of persistent organic pollutants in Arctic marine and freshwater biota. *Science of the Total Environment* **649**, 99–110.

Ritter, L., Solomon, K. R., Forget, J., Stemeroff, M. & O'Leary, C. 1995 A review of selected persistent organic pollutants. *International Programme on Chemical Safety (IPCS). PCS/95.39*, Vol. 65. World Health Organization, Geneva, p. 66.

Safe, S. 1990 Polychlorinated biphenyls (PCBs), dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs), and related compounds: Environmental and mechanistic considerations which support the development of toxic equivalency factors (TEFs). *Critical Reviews in Toxicology* **21**(1), 51–88.

Sakai, S., Ukai, T., Takatsuki, H., Nakamura, K., Kinoshita, S. & Takasuga, T. 1999 Substance flow analysis of coplanar PCBs released from waste incineration processes. *Journal of Material Cycles and Waste Management* **1**, 62–74.

Sakai, S.-I., Hayakawa, K., Takatsuki, H. & Kawakami, I. 2001 Dioxin-like PCBs released from waste incineration and their deposition flux. *Environmental Science & Technology* **35**(18), 3601–3607.

Sevin, S., Kuzukiran, O., Yurdakok-Dikmen, B., Tutun, H., Aydin, F. G. & Filazi, A. 2018 Selected persistent organic pollutants levels in the Ankara River by months. *Environmental Monitoring and Assessment* **190**, 1–7.

Shakeri, A., Shakeri, R. & Mehrabi, B. 2015 Potentially toxic elements and persistent organic pollutants in water and fish at Shahid Rajaei Dam, north of Iran. *International Journal of Environmental Science and Technology* **12**(7), 2201–2212.

Shen, J., Yang, L., Liu, G., Zhao, X. & Zheng, M. 2021 Occurrence, profiles, and control of unintentional POPs in the steelmaking industry: A review. *Science of the Total Environment* **773**, 145692.

Singh, V., Bedi, J. S., Gupta, A., Gill, J. P. S. & Aulakh, R. S. 2015 Distribution of persistent organic pollutants in farm fish, sediments and water from Punjab (India). *Toxicology International* **22**, 70–74.

Singh, D. V., Upadhyay, A. K., Singh, R. & Singh, D. P. 2022 Persistent organic pollutants: Sources, impacts, and their remediation by microalgae. In: Bhat, R. A., Dervash, M. A., Hakeem, K. R. & Masoodi, K. Z. (eds.) *Environmental Biotechnology*. Apple Academic Press, pp. 57–86.

Stachniuk, A. & Fornal, E. 2015 Liquid chromatography-mass spectrometry in the analysis of pesticide residues in food. *Food Analytical Methods* **9**(6), 1654–1665.

Street, M. E. & Bernasconi, S. 2020 Endocrine-disrupting chemicals in human fetal growth. *International Journal of Molecular Sciences* **21**(4), 1430.

Suami, R. B., Sivalingam, P., Al Salah, D. M., Grandjean, D., Mulaji, C. K., Mpiana, P. T., Breider, F., Otamonga, J. P. & Poté, J. 2020 Heavy metals and persistent organic pollutants contamination in river, estuary, and marine sediments from Atlantic Coast of Democratic Republic of the Congo. *Environmental Science and Pollution Research* **27**(16), 20000–20013.

Sun, B., Li, Q., Zheng, M., Su, G., Lin, S., Wu, M., Li, C., Wang, Q., Tao, Y., Dai, L. & Qin, Y. 2020 Recent advances in the removal of persistent organic pollutants (POPs) using multifunctional materials: A review. *Environmental Pollution* **265**, 114908.

Tanabe, S., Kannan, N., Subramanian, A., Watanabe, S. & Tatsukawa, R. 1987 Highly toxic coplanar PCBs: Occurrence, source, persistency and toxic implications to wildlife and humans. *Environmental Pollution* **47**(2), 147–163.

Tang, K. H. D. 2021 Interactions of microplastics with persistent organic pollutants and the ecotoxicological effects: A review. *Tropical Aquatic and Soil Pollution* **1**(1), 24–34.

Thayer, K. A., Heindel, J. J., Bucher, J. R. & Gallo, M. A. 2012 Role of environmental chemicals in diabetes and obesity: A National Toxicology Program workshop. *Environmental Health Perspectives* **120**, 779–789.
Titchou, F. E., Zazou, H., Afanga, H., El Gaayda, J., Akbour, R. A. & Hamdani, M. 2021 Removal of persistent organic pollutants (POPs) from water and wastewater by adsorption and electrocoagulation process. *Groundwater for Sustainable Development* **13**, 100575.
Tripathi, S., Chandra, R., Purchase, D., Bilal, M., Mythili, R. & Yadav, S. 2022 Quorum sensing – A promising tool for degradation of industrial waste containing persistent organic pollutants. *Environmental Pollution* **292**, 118342.
Trojanowicz, M. 2020 Removal of persistent organic pollutants (POPs) from waters and wastewaters by the use of ionizing radiation. *Science of the Total Environment* **718**, 134425.
Trojanowicz, M., Bartosiewicz, I., Bojanowska-Czajka, A., Szreder, T., Bobrowski, K., Nałęcz-Jawecki, G., Męczyńska-Wielgosz, S. & Nichipor, H. 2020 Application of ionizing radiation in decomposition of perfluorooctane sulfonate (PFOS) in aqueous solutions. *Chemical Engineering Journal* **379**, 122303.
Tsiantas, P., Tzanetou, E. N., Karasali, H. & Kasiotis, K. M. 2021 A Dieldrin case study: Another evidence of an obsolete substance in the European soil environment. *Agriculture* **11**(4), 314.
Tu, Z., Qi, Y., Qu, R., Tang, X., Wang, Z. & Huo, Z. 2022 Photochemical transformation of hexachlorobenzene (HCB) in solid-water system: Kinetics, mechanism and toxicity evaluation. *Chemosphere* **295**, 133907.
Tuppurainen, K., Halonen, I., Ruokojärvi, P., Tarhanen, J. & Ruuskanen, J. 1998 Formation of PCDDs and PCDFs in municipal waste incineration and its inhibition mechanisms: A review. *Chemosphere* **36**(7), 1493–1511.
Unyimadu, J. P., Osibanjo, O. & Babayemi, J. O. 2017 Selected persistent organic pollutants (POPs) in water of River Niger: Occurrence and distribution. *Environmental Monitoring and Assessment* **190**, 1.
Vikrant, K., Tsang, D. C. W., Raza, N., Giri, B. S., Kukkar, D. & Kim, K.-H. 2018 Potential utility of metal–organic framework-based platform for sensing pesticides. *ACS Applied Materials & Interfaces* **10**(10), 8797–8817.
Wacławek, S., Krawczyk, K., Silvestri, D., Padil, V. V., Řezanka, M., Černík, M. & Jaroniec, M. 2022 Cyclodextrin-based strategies for removal of persistent organic pollutants. *Advances in Colloid and Interface Science* **310**, 102807.
Waggott, A. & Wheatland, A. B. 1978 Contribution of different sources to contamination of surface waters with specific persistent organic pollutants. In: Hutzinger, O., Van Lelyveld I. H. & Zoeteman, B. C. J. *Aquatic Pollutants*. Pergamon, Oxford, pp. 141–168.
Wagner, S. & Schlummer, M. 2020 Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resources, Conservation and Recycling* **158**, 104800.
Wagner, M., Andrew Lin, K.-Y., Oh, W.-D. & Lisak, G. 2021 Metal-organic frameworks for pesticidal persistent organic pollutants detection and adsorption – A mini review. *Journal of Hazardous Materials* **413**, 125325.
Wang, X., Wang, C., Zhu, T., Gong, P., Fu, J. & Cong, Z. 2019 Persistent organic pollutants in the polar regions and the Tibetan Plateau: A review of current knowledge and future prospects. *Environmental Pollution* **248**, 191–208.
Weber, R. 2007 Relevance of PCDD/PCDF formation for the evaluation of POPs destruction technologies–review on current status and assessment gaps. *Chemosphere* **67**(9), S109–S117.
Weber, R., Schlumpf, M., Nakano, T. & Vijgen, J. 2015 The need for better management and control of POPs stockpiles. *Environmental Science and Pollution Research* **22**(19), 14385–14390.
Weber, R., Herold, C., Hollert, H., Kamphues, J., Ungemach, L., Blepp, M. & Ballschmiter, K. 2018 Life cycle of PCBs and contamination of the environment and of food products from animal origin. *Environmental Science and Pollution Research* **25**(17), 16325–16343.
Winkler, J. 2015 High levels of dioxin-like PCBs found in organic-farmed eggs caused by coating materials of asbestos-cement fiber plates: A case study. *Environment International* **80**, 72–78.
Yilmaz, B., Terekeci, H., Sandal, S. & Kelestimur, F. 2020 Endocrine disrupting chemicals: Exposure, effects on human health, mechanism of action, models for testing and strategies for prevention. *Reviews in Endocrine and Metabolic Disorders* **21**(1), 127–147.
Yusuf, K., Okolie, B. & Aderibigbe, A. 2018 Presence of polycyclic aromatic hydrocarbons (PAHs) in water and sediment from Owo River and Ologe Lagoon: a focus on distribution, source apportionment, human and ecological risk assessment. In: Ramasami, P., Gupta Bhowon, M., Jhaumeer Laulloo, S. & Li Kam Wah, H. (eds.). *Chemistry for a Clean and Healthy Planet*. ICPAC 2018. Springer, Cham, pp. 517–538.
Zhang, Q., Wang, X., Zhu, J., Li, Z. & Wang, Y. 2018 Occurrence and risk assessment of persistent organic pollutants in a branch of the Grand Canal in Hangzhou, China. *Environmental Monitoring and Assessment* **190**(4), 211.
Zhu, J. X. & Kang, S. G. 2014 Development and Application of Plasma Technology for POPs Waste Treatment in China. *Advanced Materials Research*, **878**, 638–644.
Zimmerman, L. R., Thurman, E. M. & Bastian, K. C. 2000 Detection of persistent organic pollutants in the Mississippi Delta using semipermeable membrane devices. *Science of the Total Environment* **248**(2–3), 169–179.

First received 1 November 2023; accepted in revised form 19 January 2024. Available online 13 February 2024