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REVIEW ARTICLE

Persistent organic pollutants: Environmental impact assessment, mechanisms of transport, and natural degradation approaches

Yeşim DEDE SAĞSÖZ [1], Damla MUSTAFAOĞLU [1*]

[1] Ataturk University, Faculty of Engineering, Erzurum, Turkiye

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ABSTRACT

Persistent Organic Pollutants (POPs) are artificial chemicals that have important consequences for human health and the environment. These chemicals are anthropogenic, i.e. they are caused by human activities and do not occur in natural forms in the environment. POPs pose a global environmental problem due to their persistence and long-distance transport. These chemicals accumulate especially in the adipose tissue of living organisms and are transferred to the upper layers of the food chain. Since they are stable and strong chemicals, it is very difficult for them to be broken down by biological and chemical means. Considering the large-scale effects of POPs, effective measures for their control require international co-operation and policy development. The Stockholm Convention and similar international agreements cover legal regulations regarding the production, use, and release of persistent organic pollutants (POPs) to ensure their control. To reduce the potential risks of POPs on human health and the environment, optimal solutions should be developed, and management plans should be established accordingly. These solutions are necessary to prevent the long-term persistence and biomagnification effects of POPs, which pose serious threats to ecosystems and human health.

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INTRODUCTION

Persistent Organic Pollutants (POPs) are high-risk chemicals that have toxic effects on human and environmental health, can travel long distances, accumulate in fatty tissues, and are transported up the food chain. Due to their chemical properties, these chemicals, traces of which are found not only in the places where they are produced but also in places where they are never produced or even used, are known as substances that pose a danger not only nationally but also globally. POPs are compounds that cause environmental pollution and toxicology due to human activities [1-2]. Once applied to the receiving environment, they can remain in the receiving environment for a long time, even at low concentrations, due to their biological and chemical stability. They have low volatility and low solubility in water. Due to their lipophilic properties, they accumulate in the fatty tissue of all living organisms, including humans. As a result of this accumulation, they cause high acute or chronic toxic effects on humans even after a long period. [1]. While some POPs are intentionally produced for use in industry and agriculture, others are generated as unintended by-products from industrial processes, particularly those involving high-temperature combustion [2]. The three main factors that play a role in characterizing these compounds as hazardous are toxicity, persistence, and bioaccumulation. The most important of these factors in terms of hazard is bioaccumulation. Due to bioaccumulation, these pollutants can have great destructive effects not only on the life of the living beings in the period they are formed or produced but also on the life of future generations [3]. To eliminate this global problem impacting both people and the ecosystem, 90 countries, primarily the United States and the European Community, signed the United Nations Convention for the first time in Stockholm in May 2001. According to this agreement, called the Stockholm Convention, countries agreed to prevent the output, use and release of 12 main POPs (polychlorinated biphenyls (PCBs), dichlorodiphenyltrichloroethane (DDT), aldrin, endrin, chlordane, dieldrin, heptachlor, toxaphene, hexachlorobenzene (HCB), mirex, dioxin and furan (PCDD/Fs)). In addition, the research process is ongoing to identify other possible POPs. POPs, which became widely used during the period of increased industrial production, are toxic chemicals that can be transported by wind and water, thereby adversely affecting human health and the ecology even at locations far from the point of release. POPs, which have a long persistence in the environment, collect in fatty tissue and can be transported by bioaccumulation along the food chain. Many of these chemicals have been intentionally

* Corresponding Author: damla.mustafaoglu17@ogr.atauni.edu.tr (Damla MUSTAFAOĞLU)

used as pesticides and disease control (e.g., the use of DDT against mosquito-borne malaria) and to provide insulation in insulation materials (e.g., PCBs), while some POPs have been released into the ecology as a result of industrial sources or unintentional production as a result of incineration (e.g., dioxins and furans) [4]. POPs persist in the environment for a long duration because they are chemical substances with low biodegradability and resistance to degradation. Therefore, they are likely to be transported to various environments (air, water, soil), posing a significant environmental risk. Controlling POPs requires international cooperation and policies. Similar international agreements, such as the Stockholm Convention, include the legal regulations required to control POPs from production to release. Such international agreements are critical to reducing the global impact of POPs. [5].

AN OVERVIEW OF POPs IN NATURAL ENVIRONMENTS

POPs are substances that are very resistant to chemical and biological degradation, their most important feature is that they can remain in nature for a very long time without deterioration or decomposition. Although their solubility in water is low, they are a group of chemicals that cause harmful effects on health by being soluble and accumulating in fat and therefore in tissues containing fat [3]. POPs resist to chemical, photolytic and biological degradation when released into nature. Therefore, they remain intact in nature for long periods. POPs are generally organic compounds of anthropogenic origin [6]. Persistent Organic Pollutants cannot form chemical bonds with the material to which they are added, and therefore are organic compounds that are continuously released into the environment via the material, are resistant to environmental decline, are persistent in the environment, exhibit long-distance transport properties, can accumulate in human and animal tissues. POPs enter a natural environment through various processes, including the combustion of fossil fuels in industry, commercial agricultural applications, and unintentional by-products of industrial activities. Due to their hydrophobic properties, POPs readily bind to particulate matter and subsequently settle in aquatic systems such as lakes, rivers, and oceans. Over time, these pollutant-laden particles accumulate in sediments, where they persist due to their long half-lives and resistance to degradation. Sediments not only serve as reservoirs for these pollutants but also contribute to their redistribution within the environment over time [7]. Figure 1 illustrates the primary sources of POPs propagation.

A significant portion of POPs originate from industrial chemicals or pesticides. Another portion is soot, compounds formed as by-products of the combustion of certain pesticides or wastes [8]. Figure 2 presents the types of POPs.

POPs have become a growing global focus. To prevent their release into the environment or mitigate their impacts, international agreements and organizations have taken action. Agreements such as the Regional UNECE Protocol, the Convention on Long-Range Transboundary Air Pollution, and the Stockholm Convention have introduced strict regulations for the control of POPs [9]. Table 1 shows the POP list in accordance with the Stockholm Convention came into force on 17.05.2004 with the aim of informing the world about the negative effects of POPs. Türkiye signed this convention on May 23, 2001, and the convention entered into force on October 14, 2009, with the approval of the Turkish Grand National Assembly. Although many POP compounds are known to exist in nature in different forms, some of these pollutants are considered a priority in the convention. The POP compounds identified as a priority are chlorinated pesticides such as dieldrin, aldrin, DDTs, chlordane, heptachlor (HEPT), endrin, mirex, and 2-toxaphene; HCB, PCBs and hexabromobiphenyl used as industrial products, polychlorinated dibenzofurans (PCDFs) and polychlorinated dibenzo-p-dioxins (PCDDs) formed as by-products of industrial production [10].

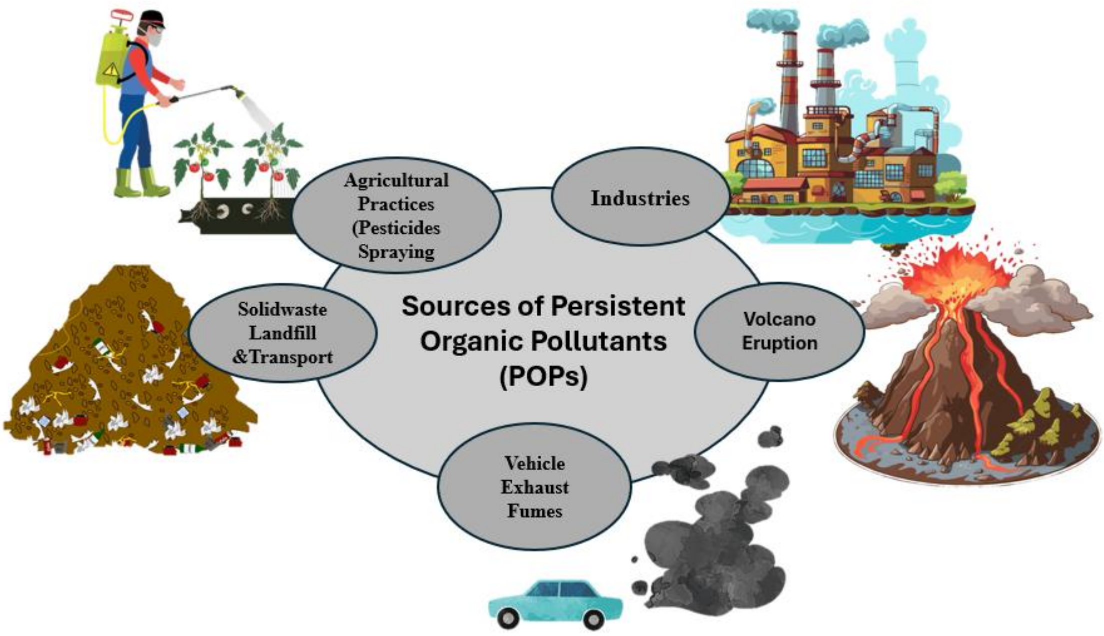

Figure 1. Primary sources of POPs

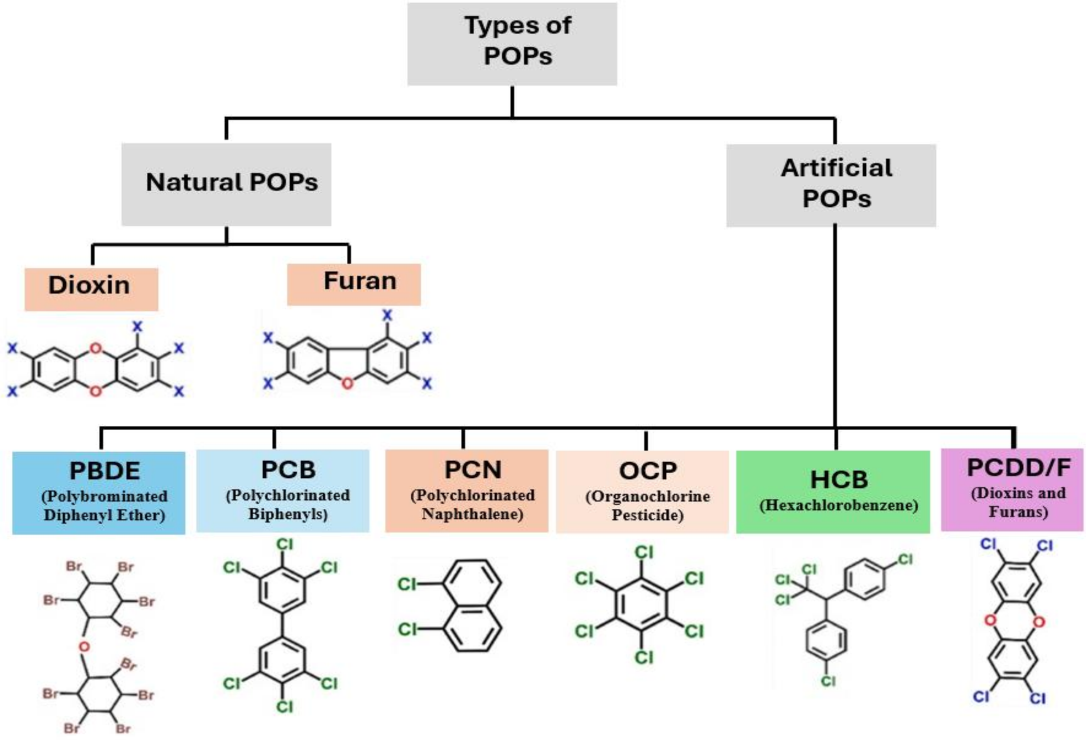

Figure 2. Types of POPs

Annex-A is the group of POPs that must be eliminated and banned. Annex-B is the group of POPs that require restriction and limitation. Annex-C includes POPs that have unintentional production and need to be reduced. The five important objectives of the Stockholm Convention are as follows;

- To eliminate hazardous POPs
- To aid the transition to secure alternatives
- To aim to control new POPs
- To clean up old equipment and stocks containing POPs
- To work together for a world free of POPs worldwide [8].

The most common POPs in the environment and their sources are given below.

HCB is used as a pesticide (fungicide) and industrial chemical and is also formed as a by-product in the production of some chlorinated substances. HCB remains intact in the water environment for a long duration, thus entering the food chain [11].

PCB is a general name given to more than 200 chemicals that are structurally similar but produced in different configurations and have a wide range of uses. PCBs are widely used especially in the paint industry. Although their production has been banned for many years, chemicals in this group are still used in some manufacturing processes. [12].

PCDD/Fs constitute a complex and highly toxic group of chemicals. Originally synthesized for their application as herbicides, these compounds have found extensive use in the paper industry due to their chemical properties. Their extensive use and long-lasting presence in industrial processes underscore substantial risks to both nature and well-being. These are also compounds formed as by-products of the burning of some wastes or pesticides [11]. PCDD/Fs are insoluble in water and highly soluble in oil. They are absorbed through the fatty tissues of humans and animals by adhering to organic matter and sediments in the environment. They are also non-biodegradable, very persistent, and bioaccumulated in the food chain [3].

Aldrin, Endrin, and Chlordane are included in the class of organochlorine pesticides. Like other organochlorine pesticides, their solubility in oil is quite high. On the contrary, it is accepted that they are very poorly soluble in water, which increases their permanence in the environment. After being used for a long time to kill insects such as grasshoppers, ants, mice, and other pests, all three were banned in 1979. Its harms to human health often occur through the endocrine system [13].

DDT is one of the most well-known persistent organic pollutants. Its decomposition products, DDE (dichlorodiphenyldichloroethylene) and DDD (dichlorodiphenyl-dichloroethane), are also toxic. It was used intensively to safeguard soldiers and civilians from malaria and typhus during World Conflict II. Similarly, its use in our country has continued in high amounts for years. Although its use has been banned worldwide since the beginning of the seventies, it can be detected in many environmental elements. In addition to the chemical's persistence, its continued use in some parts of the world is also a factor in this [14,15].

Dieldrin, Mirex, Heptachlor, Toxaphene: Like other pesticides, this group has also been used in the fight against pests in various areas, especially in agriculture and animal husbandry.

Hexabromobiphenyl, tetrabromodiphenyl ether and pentabromodiphenyl ether, which were added to the twelve POPs listed above at the fourth Stockholm Convention Meeting of the Parties held in Geneva in May 2009, are among the nine POPs included in this group. In the European Union, it is limited to the production of electrical appliances and flame retardant uses.

Endosulfan is a pesticide classified in the organochlorine group. Its broad spectrum of activity, especially against agricultural pests, has led to its intensive use in agriculture for many years. Another area of use is as a wood preservative. Today, it considered one of the most harmful pesticides to human health [3].

Table 1. POPs List in accordance with the Stockholm Convention

<table>
<tr><th>Annex A (Elimination)</th><th>Annex B (Restriction)</th><th>Annex C (Unintentional release)</th></tr>
<tr><td colspan="3">Original listing of POPs on the SC Annexes</td></tr>
<tr><td>DDT</td><td rowspan="10"></td><td rowspan="10">PBDF
HCB
PCDD
PCB</td></tr>
<tr><td>Aldrin</td></tr>
<tr><td>HCB</td></tr>
<tr><td>Dieldrin</td></tr>
<tr><td>Endrin</td></tr>
<tr><td>HEPT</td></tr>
<tr><td>Chlordane</td></tr>
<tr><td>Toxaphene</td></tr>
<tr><td>Mirex</td></tr>
<tr><td>PCBs</td></tr>
<tr><td colspan="3">POPs added to the SC Annexes in 2011</td></tr>
<tr><td>α- and β-hexachloroyclohexane (HCH)</td><td rowspan="8">Perfluorooctane sulfonic acid and its salts and perfluo-rooctane sulfonyl fluoride</td><td rowspan="8">Pentachlorobenzene</td></tr>
<tr><td>Endosulfan (Technical) and its related isomers</td></tr>
<tr><td>Hexabromobiphenyl</td></tr>
<tr><td>Hexabromobiphenyl</td></tr>
<tr><td>Chiordecone</td></tr>
<tr><td>Pentachlorobenzene</td></tr>
<tr><td>tetra, and pentabromodiphenyl ethers, hexa- and heptabromodiphenyl ethers (commercial octabromodiphenyl ether),</td></tr>
<tr><td>Lindane</td></tr>
<tr><td colspan="3">POPs added to the SC Annexes in 2014</td></tr>
<tr><td>Hexabromocyclododecane</td><td></td><td></td></tr>
</table>

ENVIRONMENTAL SPREAD OF POPS IN SOIL, WATER, AND AIR

Owing to their chemical stability, lipophilic properties and endurance to degradation, POPs accumulate in air, water, and soil environments and cause bioaccumulation by joining the food chain. Therefore, POPs are among the most common contaminants in the environment [16]. Following their release into the environment from sources such as wastewater discharge, fires, industrial accidents, or emissions, these compounds integrate into environmental cycles involving air, water, and soil through various natural processes. Given their chemical persistence and low aqueous solubility, residues of POPs can remain for extended periods at locations distant from their sources. Studies have shown that in aquatic systems, the ultimate repository for these pollutants is often the sediment at the bottom [17,18]. The bioaccumulation of POPs in humans commonly occurs through the consumption of contaminated nourishment, with these compounds accumulating in adipose tissue due to their lipophilic nature [19]. The environmental cycle of POPs is given in Figure 3.

POPs are spread globally through both abiotic and biotic components of ecosystems [20]. POPs have different chemical-physical properties that determine their behavior. POPs are grouped as single and multiple short-range transporters, fliers, and swimmers. [21]. POPs undergo minimal degradation, which contributes to their determination in the environment. These compounds can be transported over long spans via atmospheric or aquatic pathways, reaching areas far from their sources before being deposited [22]. In the last decade, POPs have received significant global attention. Several international agreements and protocols have been implemented, requiring coordinated efforts and actions of countries to reduce or prevent the release of these chemicals into the environment. Among the most important of these is the UNECE Long-Range Transboundary Air Pollution Protocol (CLRTAP) for POPs, as well as the Stockholm Convention on Persistent Organic Pollutants. There are strict international sanctions for POPs chemicals, which are 12 initial and 16 newly added chemicals under the Stockholm Convention and 16 chemicals under the UNECE Protocol [9]. Türkiye signed the Stockholm Convention on 23.05.2001 to restrict and ban the production and use of 23 POPs. Each signatory country to the Stockholm Convention is obliged to implement measures deemed appropriate to control emissions of these chemicals within its scope. In order to accurately assess environmental risks, reliable monitoring is essential to evaluate the long-range transport, toxicity, ecotoxicity, bioconcentration and bioaccumulation factors of these substances. Furthermore, to formulate effective strategies, historical data on these compounds must be considered, and their concentrations in environmental media -such as air, water, and soil- should be continuously monitored to assess future trends [23].

ADVERSE ENVIRONMENTAL IMPACTS OF POPS

POPs are chemicals with a strong affinity for biological macromolecules including nucleic acids, proteins and lipids. In this case, they disrupt homeostasis and genotoxicity in living organisms [24]. Although the risks of POPs on human and environmental health may vary, they have four common features. Living organisms are exposed to POPs through various routes such as ingestion, inhalation, transfer, and biomagnification [25]. As a result of POPs passing into water resources, the consumption of prey contaminated with chemicals in aquatic ecosystems, the accumulation of these chemicals in sediment, and the uptake of residues suspended in the water column through the skin, gills, and food, pollutants are incorporated into the body of aquatic invertebrate or vertebrate species and accumulate in the target organs of the body, reaching higher concentrations in the upper trophic layers of the food chain [26]. The toxic properties of pesticides pose significant risks to both target organisms and non-target species living in the vicinity of the chemical area. Pollutants spread throughout aquatic environments and pollute both surface waters and groundwater, causing the formation of dead zones in aquatic ecosystems and thus harming fisheries [27]. PCDD/Fs enter plant-based foods because of the use of pesticides, the accumulation of dioxin-containing particles in the air on plants, and the evaporation of PCDD/Fs from soil. These substances are transported to fruits and leaves via roots. In the atmospheric route, dry gases accumulate with humidity, and dry particles accumulate. PCDD/Fs can also be passed into humans via animal products [28]. After PCDD/Fs and similar compounds enter the body, they accumulate in the animal's adipose tissue and leave the body via milking. There is direct human transfer via both routes [29]. Pathways of Exposure of Humans and the Environment to POPs are given in Figure 4.

The fact that POPs are insoluble in water, remain stable for many years, enter the food chain, and accumulate in the fatty tissues of both humans and animals due to their lipophilic nature indicates their potential to cause significant health problems.

People are often exposed to POPs through contaminated food (fish, meat, dairy products), the air they breathe or through skin contact. In the long term, these substances can accumulate in the body and weaken the immune system, disrupt hormone balance, cause infertility and cause cancer. Babies can be exposed to these poisons through breast milk and experience developmental problems.

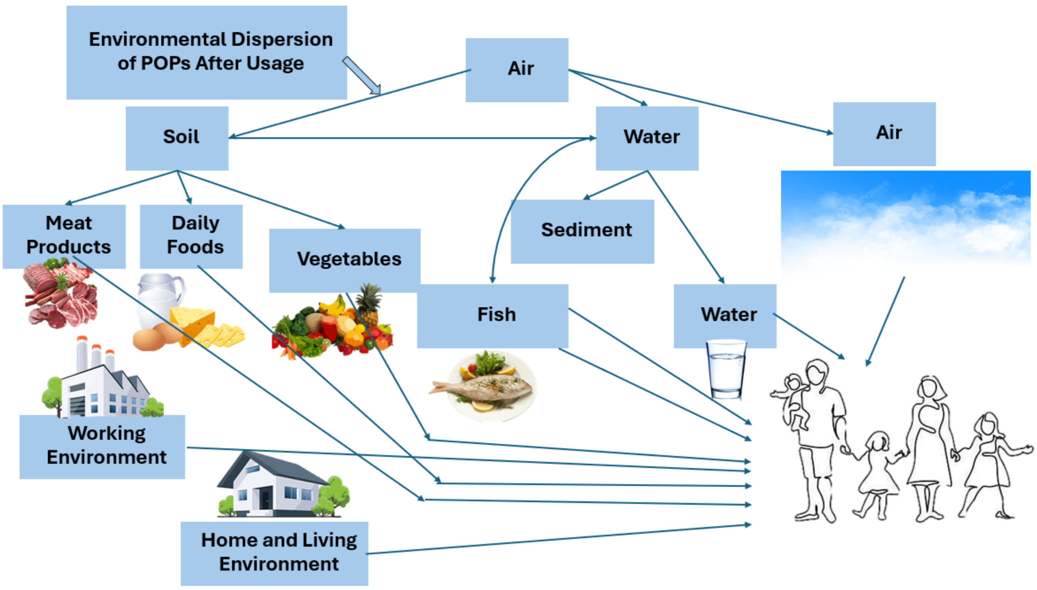

Figure 3. POPs cycle in the environment

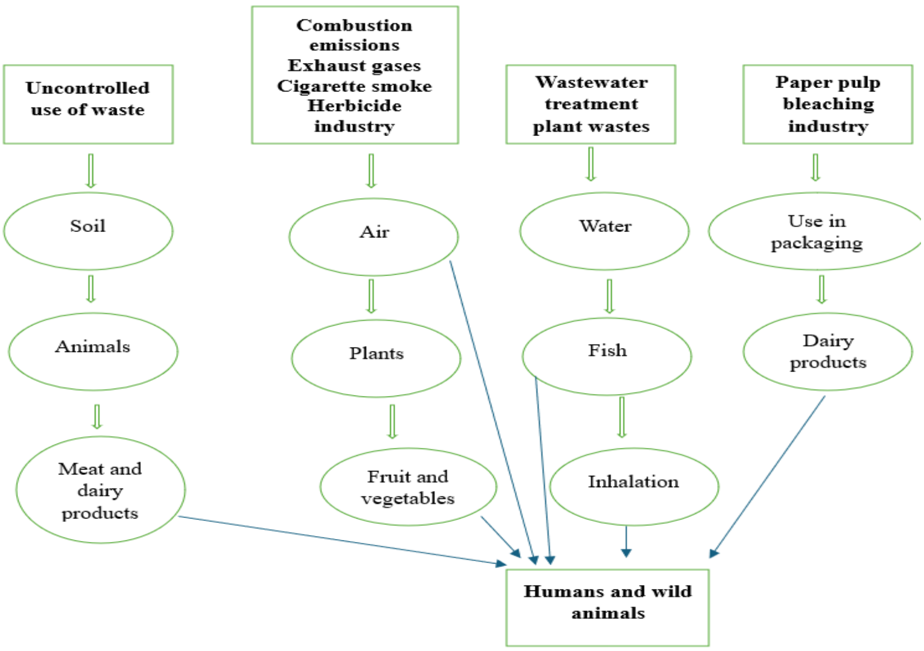

Figure 4. Routes of Human and Environmental Exposure to POPs

Animals are also seriously affected by POPs. For example, in some bird species, substances such as DDT thin eggshells, making it difficult for chicks to survive. In mammals, the risk of contracting diseases increases as the immune system weakens. They can damage the nervous system, causing paralysis, behavioural disorders and even death.

Especially animals at the top of the food chain - seals, whales and birds of prey - are the ones where POPs accumulate the most. This can sometimes even lead to mass mortality. In humans, high levels of exposure can lead to severe poisoning and even death [30].

Therefore, it is crucial to monitor their levels in the ecosystem and to implement measures to prevent or minimize their formation to protect human health and prevent environmental pollution.

DEGRADATION PROCESSES OF POPS IN THE ENVIRONMENT

Persistent Organic Pollutants (POPs) are highly resistant to degradation due to their chemical structures. The fundamental chemical structure of POPs involves the reinforcement of carbon-hydrogen bonds with halogen atoms, typically chlorine and bromine [31]. These halogen atoms enhance the chemical stability of the molecules, making it challenging for these pollutants to degrade through biological and chemical processes [32,33]. Chlorine atoms added to the POP structure increase the chemical stability of molecules by binding to the carbon skeleton [29]. As a result, POPs are resistant to environmental degradation mechanisms such as hydrolysis, photodegradation, and oxidation [34, 35]. For example, the reason why DDT (Dichloro Diphenyl Trichloroethane), which is widely used as a pesticide, does not decompose both when exposed to direct sunlight and under the influence of microorganisms is the high amount of bound chlorine atoms in its chemical structure. Due to this chemical stability, POPs persist in the environment over extended durations. In addition, the degradation products of POPs pose environmental problems. For example, DDE, a degradation product of DDT, is as persistent and toxic as DDT. Therefore, the persistence of POPs in the environment is not limited to longevity. The degradation products of POPs are also hazardous [36]. The lipophilic properties of POPs allow them to accumulate easily in the fatty tissues of organisms. These pollutants, which have low solubility in aquatic environments due to their lipophilic structure, are transferred from water to the fatty tissues of organisms [34,37,38]. Since POPs are metabolically degraded, this process continues throughout the life of a living organism. The process by which POPs remain in the body of a living organism is called bioconcentration. When these chemicals pass from one organism to another, they are transferred to the upper layers of the food chain by a process called biomagnification [39]. Knowledge of the degradation processes of these chemicals is very important to minimise the long-term hazards of POPs. Degradation generally occurs by processes such as biodegradation, physicochemical degradation and photodegradation [40]. The effect of degradation mechanisms of these chemicals can be characterised according to the specific chemical property of POPs and environmental conditions.

Photodegradation

Photodegradation is a degradation process that is accelerated by exposure to ultraviolet (UV) light. UV radiation cleaves POPs' chemical bonds, converting them into smaller, generally less harmful molecules for the environment [40]. However, some POPs are more resistant to sunlight and therefore slow to degrade under UV light [41]. In addition, the degradation products released as a result of the photodegradation degradation process may be toxic.

Biodegradation

Biodegradation is a process in which POPs are metabolized by microorganisms and converted into simpler compounds. However, due to the structural durability and toxicity of POPs, biodegradation is generally a slow and limited process. POPs are toxic to most microorganisms, making biological destruction of these pollutants difficult. In addition, POPs that undergo partial degradation by some microorganisms can turn into environmentally harmful products [42, 43, 44]. The biodegradation process also depends on factors such as pH, humidity, temperature and microorganism diversity. Therefore, environmental conditions must be optimal for the process to occur effectively [45].

Physicochemical Degradation

Physicochemical degradation, also known as abiotic degradation, primarily occurs when the physical forces of POPs are degraded by abiotic conditions and biological degradation begins [46]. Naturally, the degradation of POPs begins with photodegradation, and then continues with the hydrolysis process. The biological degradation process follows hydrolysis. All these reactions result in the degradation of POPs into compounds with lower molecular weight [47,48]. However, this mechanism is extremely slow and may take centuries to fully occur [49]. There are some variables that affect the degradation processes of POPs. These factors consist of components such as the chemical structure of POPs, microbial activity, and environmental conditions. Each of these factors is very important since they affect the degradation rate and mechanisms of POPs in different ways. Microbial activity forms the basis of biodegradation processes in the degradation of POPs. Biodegradation is influenced by the type and amount of microorganisms present in the water and soil environment [50]. The chemical structure of these substances is the most important reason for their resistance to degradation. Another reason why POPs are resistant to degradation is the halogens in their structure. [39]. These chemicals are very poorly soluble in water due to their hydrophobic properties. This makes it difficult for microorganisms to reach POPs in aqueous media [51]. Environmental factors such as humidity, pH, sunlight and temperature directly play an important role in the degradation processes of POPs. Temperature value in the environment affects biological activities and chemical reactions. Photodegradation and chemical oxidation processes are accelerated at high temperatures. Very high temperatures limit the biodegradation process. Another environmental factor that plays an significant role in the degradation of POPs is pH. POPs also differ depending on their chemical properties; for example, some pesticides degrade faster in acidic environments, while others degrade faster in basic conditions. Humidity has an important effect, especially in soil and water environments, during the biological degradation of POPs. When humidity is sufficient, microorganisms metabolize POPs [52]. Sunlight directly affects photodegradation processes. UV rays break the chemical bonds of POPs, allowing them to transform into smaller molecules. Each of these factors affects how and how quickly POPs degrade in the environment. Therefore, considering these factors is vital for developing appropriate strategies for environmental management and cleanup of POPs [53]. POPs may release toxic intermediates that need to be controlled during the degradation process. These processes are often unpredictable. Different toxic intermediates may be released for each type of POP. The presence of toxic intermediates further complicates the cleaning and disposal processes of POPs. As a result, the highly stable chemical structures of POPs and the toxic intermediates formed during the degradation processes increase the hazards of these pollutants. In order to eliminate these difficulties, innovative and effective environmental management strategies and technologies need to be developed [29, 54].

GLOBAL TRANSPORT OF POPS AND LONG-DISTANCE EFFECTS

POPs are pollutants that can reach ecosystems and human communities far away from their source regions, especially through atmospheric means [31]. Therefore, POPs are a global environmental problem rather than local pollution. The transport of POPs in the atmosphere occurs through various physical and chemical processes. These pollutants are generally volatile compounds. Since these compounds have low vapor pressure from soil, water, and plants in the source regions, they are easily evaporated and released into the atmosphere [55]. These pollutants released into the atmosphere are carried by winds and air currents and spread to different layers of the atmosphere. In addition, these pollutants travel large distances in the atmosphere under the influence of factors such as high temperature and sunlight [56]. Especially winds and atmospheric pressure cause POPs to reach distant ecosystems such as polar regions, mountain areas, and oceans [1]. Figure 5 shows the global transport of POPs.

This transport process enables POPs to spread to regions thousands of kilometres away from their original source. POPs are transported in the atmosphere and tend to concentrate in colder regions and sink to the surface, causing POPs to accumulate in cold regions [57,22]. Increasing temperatures in these regions cause these compounds to be re-released into the atmosphere, leading to a cyclical movement that allows POPs to travel large distances. This ongoing process causes POPs to accumulate, especially in sensitive ecosystems such as the polar regions [58]. This is known as the "cold trap effect" [59], where POPs condense at low temperatures and accumulate on snow and ice in the polar regions. POPs accumulate in glaciers, particularly in the Arctic and Antarctic regions [60]. When these ice masses melt, POPs are released into the oceans and other water bodies, and then into aquatic ecosystems. In polar regions, POPs cause biomagnification in the food chain. For example, POPs can be transferred from plankton to other marine organisms, birds and mammals, seriously affecting these organisms. In addition, these chemicals, which are transported over long distances, may adversely affect human health when they enter the food chain and may cause different chronic health problems [61,62].

POPs can be transported globally over long distances through atmospheric movements, ocean currents, and biological processes. This phenomenon poses a threat not only to the regions where they are produced or used but also to distant ecosystems and human communities. The widespread distribution of POPs necessitates international cooperation and strategic management approaches. At this point, effectively controlling POPs requires identifying existing strengths and weaknesses, evaluating opportunities, and analyzing potential threats. In this context, a SWOT analysis of POP management serves as a crucial guide for policymakers and environmental experts.

SWOT ANALYSIS FOR POPS

The SWOT analysis for Persistent Organic Pollutants (POPs) is crucial for their management and control. (1) Strengths include international regulations, increasing scientific research, and the development of cleaner technologies. (2) Weaknesses involve the long-term persistence of POPs in the environment, inadequate management in some countries, and high disposal costs. (3) Opportunities consist of the development of safer alternative chemicals, international collaborations, and rising public environmental awareness. (4) Threats include the economic interests of industrial sectors, the impact of climate change on the spread of POPs, and the risk of their reintroduction into the environment through recycling processes. This analysis helps in developing effective strategies to combat POP pollution.

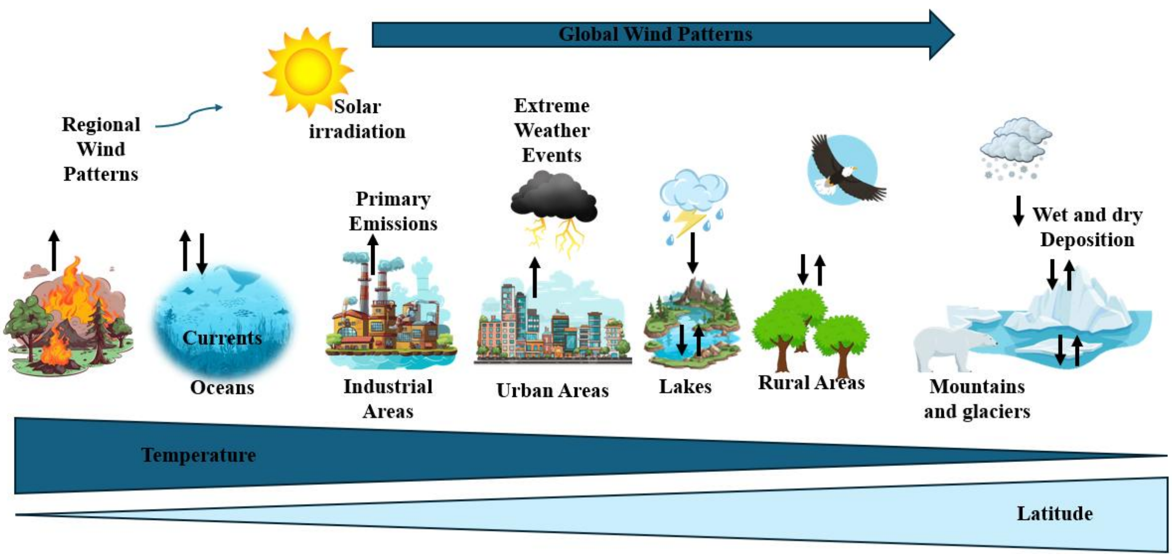

Figure 5. Figure 5. Global transport of POPs

Strengths:

- Scientific Awareness and Research: There is a large number of scientific studies on the effects of POPs. This provides a wide range of knowledge on the subject.
- International Conventions and Policies: International regulations and conventions on the subject; for example, the Stockholm Convention constitutes the legal basis for the control of POPs.
- Technological Advances: Scientific techniques (such as GC-MS, HPLC) used in the analysis and disposal of POPs are highly developed.
- Public Health and Environmental Protection Awareness: Increased environmental awareness provides an important social support for reducing the production and use of POPs.

Weaknesses:

Persistence and Transition to Biomass: The fact that POPs remain in the environment for a long time and can transition to biological bodies makes their disposal difficult.

- High Removal Costs: Disposal and removal of POPs cause very high costs.
- Lack of Information and Education: Lack of awareness and technical knowledge on POPs makes it difficult to implement effective solution policies at local and national level.
- Lack of Legislation and Inspection: In some places there is a lack of understanding and implementation of legal regulations on POPs.

Opportunities:

International Support and Financing: There are opportunities for technical and financial support provided by the UN and other international organisations, national institutions and organisations.

- Green Technologies: Enabling environment-based removal and disposal methods.
- Education and Awareness Programmes: Company and individual trainings on the scope, impact and spread of POPs can contribute to effective and sustainable solutions.
- Reuse and Conversion Techniques: New technologies can be developed to minimise the harm of POPs or to recycle them.

Threats:

- Environmental Dispersion: POPs can diffuse into the environment and threaten the environment by mixing with air, water and soil.
- Increase in Industrial Activities: Global increase in industrial activity affects the impact, transport and dispersion of POPs.
- Health and Toxicity Risks: POPs have permanent and toxic effects on living health and ecosystem.
- Global Climate Change: Climate change may increase the rate and impact of POPs transport in the atmosphere.

RECOMMENDATIONS FOR CONTROLLING AND REDUCING POPS

Given the long-distance transport and widespread impacts of POPs, effective international cooperation and policies are crucial for their management and control. International agreements like the Stockholm Convention provide the legal framework necessary to regulate the production, use, and release of POPs [53]. For these regulations to be successful, national treaties and protocols must be implemented effectively to reduce the harmful effects of POPs on a global scale. To address the long-term impacts of these chemicals, up-to-date technologies, sustainable policies, and international collaboration are essential [63].

The production and use of all types of POPs and industrial chemicals should be banned, with strict monitoring to ensure compliance. Developing and using environmentally friendly alternatives is key to reducing the release of these harmful chemicals into the environment. Additionally, industrial processes that contribute to POP emissions should be improved, with a focus on cleaner production technologies. Methods like advanced filtration systems, closed-circuit processes, and tighter emission controls are all important in reducing POP pollution. Alongside these approaches, it's crucial to integrate various treatment methods into waste management systems to efficiently remove POPs. Techniques such as chemical oxidation, adsorption, and membrane filtration should be used in combination to address this challenge. Advanced oxidation processes (AOPs), bioremediation, phytoremediation, and catalytic degradation have shown promise as solutions for breaking down persistent pollutants and minimizing their impact on the environment [64].

These methods rely on different degradation processes, such as oxidation reactions that produce reactive species capable of breaking down the complex molecules of POPs, reducing their toxicity and persistence. Bioremediation and phytoremediation use microorganisms or plants, respectively, to degrade or absorb POPs, offering a more eco-friendly approach to cleaning up contaminated environments.

Raising awareness about the dangers of POPs and the control strategies available is also important. In addition to technological and regulatory measures, public understanding and involvement are necessary for more effective environmental protection. Ultimately, the goal is to reduce the release of these harmful chemicals, implement efficient removal strategies, and create a cleaner, healthier environment for future generations. Tackling POPs requires a collective effort on both national and international levels, with legal frameworks, scientific innovation, and public engagement working together to create lasting change.

AUTHOR CONTRIBUTIONS STATEMENT

In this review article, both authors contributed equally and collaboratively throughout the development process. They jointly conceptualized the research focus and scope, meticulously conducted an extensive literature review, and co-authored each section, ensuring depth and consistency across the manuscript. Their contributions included synthesizing findings, structuring arguments, and aligning content with current scientific perspectives. Furthermore, they worked together in critically revising and refining the manuscript to enhance its clarity, coherence, and analytical rigor. The authors also jointly undertook the translation and final formatting to ensure linguistic precision and accessibility for an international audience.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There is no need to obtain permission from the ethics committee for the article prepared.

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