Persistent Organic Pollutants in Water and their Microalgae Based Bioremediation

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This appraisal overviews Persistent Organic Pollutants and suggests a novel approach to their bioremediation using algae as an agent. Compared to older techniques using different bacteria, a greenway for wastewater treatment is more environmentally sustainable and friendlier. It has a lot of potential to use new bioremediation technology that uses cyanobacteria and algae to remove variety of organic pollutants. Several organisms' health and well-being may be at risk due to the abundance of organic pollutants in the environment. Household garbage, agriculture, and industry are some of the numerous man-caused contributors to organic pollutants that pollute water across the planet. Wastewater needs to be cleaned before it may be discharged into rivers. As algae-based wastewater treatment systems don't produce any secondary pollutants and are environmentally sustainable, they are growing in popularity. A variety of organic pollutants can be absorbed and accumulated by algae and cyanobacteria at different rates, contingent upon the type of contaminant, the physio-chemical assets of waste water, as well as the specific species of algae involved. Moreover, phytoremediation is a more affordable option for breaking down organic pollutants than traditional methods. Algal biomass produced through phycoremediation might also play a significant role in the bioenergy value chain. Hence the emphasis of this paper is on an over view of Persistent Organic Pollutants, cyanobacteria and microalgae species, which have the potential to rid water systems of several organic pollutants.

Keywords: Bioremediation; Biodegradation; Microalgae; Persistent Organic Pollutants.

Humans have manufactured and commercialized millions of tones of Persistent Organic Pollutants (POPs) for various agricultural, industrial and consumer applications due to growing population, its selective demand and industrialization around the world. The development is accompanied by a notable rise in the amount of organic contaminants that have contaminated water streams. However, these substances have been revealed to be persistent, bioaccumulative, toxic, and ubiquitous in the global environment[1]. Toxic substances with a heterogeneous carbon base, such as PCBs, DDT, and Aldrin, are known as POPs and have a negative impact on both the environment and human health. POPs can build up in the environment and can be transferred up the food chain from one species to another[2]. Twelve POPs, commonly used pesticides, industrial chemicals,

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or their byproducts, were first identified by the Stockholm Convention, which was accepted by the United Nations Environment Programme (UNEP) for POP regulation. This recognition imposed a worldwide ban on the POPs[3].

The generation of POPs, especially in water pollution, has increased due to the rapid rise of urbanization and industry. Water pollution is one of the most important environmental issues facing the world today. Nevertheless, because of their excessive use, the balance between their positive and negative impacts has been upset, seriously harming the ecosystem[4]. The accumulation of plenty of organic substances from urban runoff, industrial waste, and raw or treated domestic and agricultural sewage can lead to pollution in water systems because of their toxicity, bioaccumulation tendency, persistence, and vulnerability to long range transport and deposition in atmosphere[5]. Many remediation techniques, including adsorption and ultrasonic irradiation, have been developed to counteract these harmful consequences. However, though, the majority of them are not economical or environmentally friendly. As bioremediation is less costly and more environmentally friendly than these remediation techniques, it has emerged as a viable substitute[6].

Microalgae-based biodegradation of POPs in water is a promising and environmentally friendly approach to address the growing concern of water pollution. These are a class of hazardous substances that withstand deterioration and endure long periods of time in the environment. Aquatic ecosystems, human health, and the planet's general health are all seriously threatened by these pollutants. Microalgae, microscopic photosynthetic organisms, have emerged as powerful tools in environmental remediation due to their unique metabolic capabilities and adaptability to various environmental conditions. They play a crucial role in the biodegradation of POPs by utilizing these pollutants as a source of carbon for growth and energy assembly. Through the metabolic processes of microalgae, complex organic substances are broken down into simpler and less harmful forms. Owing to their adaptable metabolism and little requirement of nutrients (Sunlight and CO_2), microalgae have garnered enough attention recently to be considered as a viable bioremediation alternative. The remediation techniques based on microalgae and cyanobacteria are more ecologically sound and can be combined with a number of different technologies, including those that produce bio-fuel and reduce carbon emissions[7]. Because they are trophically independent of both carbon and nitrogen, microalgae offer a potential new avenue for the bioremediation of distillery wastewaters. More likely, it's a novel bioremediation method that uses cyanobacteria and algae to eliminate organic contaminants. As a result, it is a greenway that cleans wastewater[8].

Sources of POPs

POPs are a group of hazardous chemicals that resist environmental degradation and can persist in the environment for extended periods. These pollutants originate from various sources, both natural and anthropogenic as mentioned in Figure 1. The primary sources of POPs include industrial processes, agricultural practices, waste management, and combustion of fossil fuels, transportation, accidental releases and natural sources[9].

Industrial Processes include chemical manufacturing and metal production along with processing. The production of certain chemicals, including pesticides, herbicides, and industrial chemicals, can result in the release of POPs into the environment. Certain industrial activities, such as metal smelting and processing, can lead to the emission of POPs[10]. Non-judicial application of pesticides, herbicides and fertilizers for increased crop production has been the issue of concern. The use of certain persistent pesticides and herbicides in agriculture can contribute to the presence of POPs in soil and water. Some fertilizers may contain POPs or contribute to their formation in the environment. Waste incineration and landfills which includes Burning of waste, especially in uncontrolled or inefficient incinerators, can release POPs into the air. POPs can seep into the groundwater and soil as a consequence of poor landfill disposal of plastics, electronic junk, and other things. Due to incomplete combustion, POPs may arise and are released during the burning of fossil fuels including coal, oil, and natural gas, particularly if the combustion process is not completed. Exhaust emissions from vehicles, especially those using leaded gasoline or diesel, can contribute to the release of POPs into the atmosphere. Accidents during the production, transportation, or use of chemicals can lead to the sudden release of POPs into the environment. The release of POPs can occur during oil spills, leading to contamination of water bodies. Some consumer products, such as certain flame retardants used in textiles and electronics, may contain or result in the release of POPs. POPs can travel long distances through the atmosphere and deposit far from their original sources. This process, known as the "grasshopper effect," contributes to the global distribution of POPs[11]. The historical use of certain POPs, such as polychlorinated biphenyls (PCBs) and organochlorine pesticides, has led to persistent legacy contamination in the environment. Some POPs, such as polycyclic aromatic hydrocarbons (PAHs), can be released during volcanic eruptions. Natural processes, such as the breakdown of organic matter by bacteria, can also release certain POPs. Efforts to control and reduce POPs often involve international agreements, such as the Stockholm Convention on Persistent Organic Pollutants, which aims to eliminate or restrict the production and use of specific POPs to minimize their environmental impact. Additionally, stringent regulations and sustainable practices in various industries are crucial for preventing the further release of POPs into the environment.

Humans are exposed to POPs, or halogenated xenobiotic chemicals, through a variety of commodities from both point and nonpoint sources. As per the rules issued by the Environmental Protection Agency (EPA), there is a significant prevalence of diseases in the marine and coastal ecosystems that are caused by these toxins. Individuals who have used the synthetic substances to adapt to modern lifestyles are intentionally discharged into the atmosphere. POPs are divided into 4 categories: (i) the most hazardous substances, whose usage and manufacture are restricted; (ii) the medium-level compounds that are only permitted to be used during manufacture; (iii) unintended chemical release that occurs during manufacture; (iv)and the application of chemicals under investigation[12].

Types of POPs

POPs are divided in to mainly two classes: (i) Intentionally Produced POPs- The desired products are created through chemical processes, and because they contain a chlorine atom that is highly lipophilic and neurotoxic, they are referred to as organochlorine compounds (OCs). These can be further separated into two categories based on how they are used: Industrial chemicals and insecticides containing organochlorines: Organochlorine pesticides (DDT, Mirex, Endrin, Dieldrin, Heptachlor, Chlordane, Aldrin and Hexachloro benzene) are the compounds which are used to kill pesticides[13]. The significant category of particular wastes known as industrial chemicals includes polychlorinated biphenyls (PCBs), which were identified as pollutants in 1966. They are employed in a variety of preparations, including resins, detergents, dyes, sanitizers, plasticizers, antioxidants, and surfactants. (ii) Unintentionally Produced POPs- The majority of them are unwanted byproducts of burning or other chemical reactions that include chlorine or compounds chlorinated. The three main groups are dioxins, furans, and polycyclic aromatic hydrocarbons (PAHs). Polycyclic Aromatic Hydrocarbons (PAHs) belongs to broad family of chemical compounds includes compounds having two or more fused aromatic rings, ranging from derivatives of two-ring naphthalene to intricate structures with as many as ten rings. PAHs are released into the environment by both natural and man-made sources[14]. Due to their comparable chemical characteristics and harmful consequences, dioxins and furans (also known as chlorinated dibenzofurans) have been a serious worry for many years. PCB-126 and 2, 3, 7, 8-TCDD; 2, 3, 7, 8-TCDF are a few of these compounds. Dioxin-like PCBs (DLPCBs) are a novel class of PCBs that comprise a particular subset of PCBs. Rather of coming from Mother nature, human-caused emissions and operations emit dibenzofurans (PCDFs) and polychlorinated dioxins (PCDDs) as previously reported[15]. It was decided by the Stockholm Convention to reduce or eliminate the manufacture, use, and emission of 12 important POPs, which are commonly known as "The Dirty Dozen." After two revisions, ten additional compounds were finally added to the POPs group[16] (year 2009 and 2011) as mentioned in Table.1. POPs are a group of hazardous chemicals that resist environmental degradation, persist in the environment, bioaccumulate in living organisms, plus create a range of unfavorable consequence on person's wellbeing and ecosystems. The Stockholm Convention on POPs identifies and classifies several types of it based on their chemical structures and properties. The major types of POPs include:

Organochlorine Pesticides

These includes DDT (Dichlorodiphenyltri-chloroethane) and Aldrin and Dieldrin. Historically used as an insecticide, DDT is known for its persistence in the environment and its bioaccumulation in the fatty tissues of organisms. Used as insecticides, these chemicals are persistent and have been banned in many countries due to their harmful effects. It was historically used as an insecticide to control malaria and other insect-borne diseases. It was also used in agriculture to protect crops from pests. It is associated with endocrine disruption, nervous system effects, and has been classified as a possible human carcinogen. Prolonged exposure can lead to adverse effects on the female reproductive system leading to infertility and cancer[17].

Polychlorinated Biphenyls (PCBs)

PCBs are a group of synthetic organic compounds that were widely used as coolants and lubricants in electrical equipment, as well as in various industrial applications. They are highly persistent and can accumulate in the environment and biota. PCBs were widely used as coolants and lubricants in electrical equipment, such as transformers and capacitors. They were also used in hydraulic fluids and as additives in paints and sealants. PCBs are known to have a range of toxic effects, including carcinogenicity, endocrine disruption, and developmental and reproductive toxicity. Prenatal exposure can lead to developmental issues in children[18].

Polybrominated Diphenyl Ethers (PBDEs)

PBDEs are flame retardants used in a variety of consumer products, such as electronics, textiles, and plastics. These were utilized as fire reducers in a range of consumer goods, such as furniture, textiles, and electronics. PBDEs are associated with neuro developmental effects, endocrine disruption, and potential carcinogenicity. Prenatal exposure can lead to developmental issues in children. They have been found to persist in the environment and can accumulate in human and animal tissues[19].

Polycyclic Aromatic Hydrocarbons (PAHs)

PAHs are a group of organic compounds containing multiple fused aromatic rings. They are produced by incomplete combustion of organic materials, such as fossil fuels and wood. Some PAHs are known carcinogens and can persist in the environment[20].

Hexachlorobenzene (HCB)

HCB is a chlorinated aromatic compound that has been used as a fungicide. It is persistent and can bio-accumulate in the food chain. It was used as a fungicide, especially for controlling seed and soil-borne fungi in agriculture. HCB is associated with liver and kidney damage, as well as immunotoxic effects. Long-term exposure can lead to neurological symptoms and developmental issues[21].

Chlorinated Paraffins

Chlorinated paraffins are complex mixtures of chlorinated hydrocarbons used as flame retardants and plasticizers. They are persistent and can accumulate in aquatic environments. These have been used as flame retardants in various products, such as plastics, rubber, and textiles. Chlorinated paraffins are associated with liver toxicity, reproductive and developmental effects, and potential carcinogenicity[22].

Dioxins and Furans

These are a family of highly toxic and persistent compounds formed as by-products of various industrial processes, such as waste incineration and certain chemical manufacturing. They are unintentional by-products of industrial processes, waste incineration, and certain chemical manufacturing processes. Dioxins and furans are associated with a range of health effects, including carcinogenicity, immunotoxicity, and reproductive and developmental toxicity. Long-term exposure can lead to chloracne and other skin disorders[23].

Endosulfan

It is an organochlorine insecticide that has been widely used in agriculture. It is known for its persistence and potential health and environmental impacts[24].

Perfluorooctane Sulfonate (PFOS) and Perfluorooctanoic Acid (PFOA)

These are perfluoroalkyl substances (PFAS) used in various industrial processes, including the production of non-stick coatings and water- and stain-resistant treatments. They are persistent and have risen environmental and health concerns. These two were used in manufacturing of foams for fire-fighting, water- and stain-resistant treatments, and non-stick coatings. PFOS and PFOA are associated with immune system effects, developmental and reproductive toxicity, and potential carcinogenicity. They are also associated to unfavorable impacts on the thyroid and liver via drinking water[25].

It's important to note that regulatory measures, including international agreements like the Stockholm Convention, aims to phase out the production and utilization of these POPs to protect human health and the environment. Ongoing research continues to enhance our understanding of the risks associated with these substances and inform strategies for their management and remediation. Stockholm Convention, which attempts to eradicate or limit the manufacture and use of particular POPs to safeguard human well-being and the ecosystem, are among the measures taken to lessen the detrimental effects of POPs. Regulatory measures, research, as well as public awareness campaigns are essential components of global strategies to address the issue of persistent organic pollutants.

Effect of POPs

POPs are known for their toxic effects on both the environment and human health[26]. Health issues and complications are caused in various organ systems of the human body due to exposure to POPs (Figure 2). These effects result from the persistence, bioaccumulation, and biomagnification of these substances in the food chain. Different POPs exhibit various toxicological properties, but common adverse effects include: endocrine disruption, carcinogenicity, reproductive and developmental Effects, genotoxicity, neurotoxicity, immunotoxicity, hepatotoxicity, Cardiovascular Effects, developmental delays and behavioral issues[27]. Many POPs have endocrine-disrupting properties, meaning they can interfere with the endocrine system's normal functioning. This disruption can lead to hormonal imbalances and adverse effects on reproductive health, development, and metabolism. Some POPs, such as certain polychlorinated biphenyls (PCBs) and dioxins have been classified as known or suspected human carcinogens. Prolonged exposure to these substances has been associated with an increased risk of various cancers[28]. POPs can have detrimental effects on reproductive health, leading to reduced fertility, altered hormone levels, and impaired development of the reproductive organs. Exposure during pregnancy can also result in developmental abnormalities in the fetus[29]. Certain POPs, including organochlorine pesticides, have neurotoxic effects, affecting the nervous system. Neurological disorders, cognitive impairments, and behavioral abnormalities can result from exposure to these substances. POPs can compromise the immune system, making individuals more susceptible to infections and

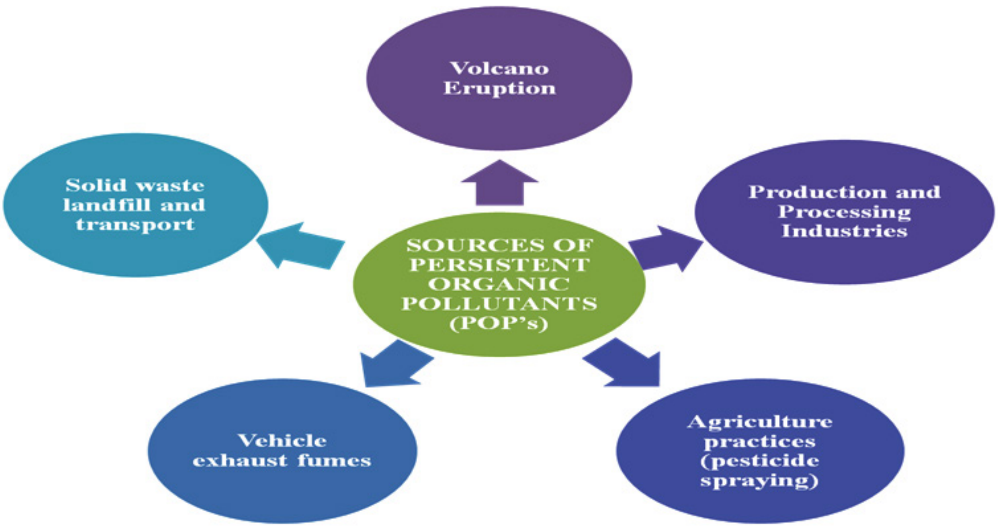

Fig. 1. Various sources of persistent organic pollutants (POP's).

Table 1. List of POPs given by Stockholm Convention

Chemical	Category
As per the 2001 amendment (The Dirty Dozen)	
Polychlorinated Biphenyls (PCB)	Industrial Waste/ By-product
Polychlorinated dibenzofurans (PCDF)	By-product
Chlordane	Pesticide
Mirex	Pesticide
Endrin	Pesticide
Aldrin	Pesticide
Dieldrin	Pesticide
Hexachlorobenzene (HCB)	Pesticide
Heptachlor	Pesticide
Toxaphene	Pesticide
Dichlorodiphenyltrichloroethane (DDT)	Pesticide
As per the 2009 Amendment	
Lindane	Pesticide
Chlordecone	Pesticide
Pentachloro benzene	Pesticideandby-product
Alpha-Hexachlorocyclohexane	Pesticideandby-product
Beta-Hexachlorocyclohexane	Pesticideandby-product
Perfluorooctanoic acid (PFO) and Constituents Perfluorooctanesulfonylfluoride (PFOSF)	Industrial
Hexabromobiphenyl	Industrial
Hexa-bromodiphenylether (Hexa-BDE) and Hepta- bromodiphenylether (Hepta-BDE)	Industrial
Tetra-bromodiphenylether (Tetra-BDE) And Penta-bromodiphenylether (Penta-BDE)	Industrial
As per the 2011 Amendment	
Endosulfan	Pesticide

Table 2. Various POPs and their reported common uses and effects on human health

Persistent organic Pollutant (POPs)	Common Use	Health Effects	References
Biphenyls	Food preservatives, dyes, heat transfer fluids	Issues related to skin	(37)
Bisphenol A (BPA)	Water bottles, food cans	Obesity	(38)
Hexachlorocyclohexane (HCH)	Fumigants, Pesticide, personal care products	Respiratory disruptions	(3)
Chlordecone	Insecticide	Hampered infant development	(39)
Polychlorinated biphenyls (PCB)	Coolants and lubricants in transformers, capacitors, and other electrical equipment	Elevated risk of cancer	(40)
Dichlorodiphenyl Trichloroethane (DDT)	Pesticides	Obesity	(41)
Endrin	Pesticide	Acute neurological disorders	(42)
Hexachlorobenzene (HCB)	Fungicide	Thyroid dysfunction	(43)
Endosulfan and derivates	Pesticides	Cardiovascular problems	(44)
Parabens	Personal care products, cosmetics	Modified reproductive and thyroid hormones	(45)
Aldrin and dieldrin	Pesticides	Nausea	(46)
Polybrominated biphenyls (PBB)	Flame retardants	Type 2 diabetes	(47)

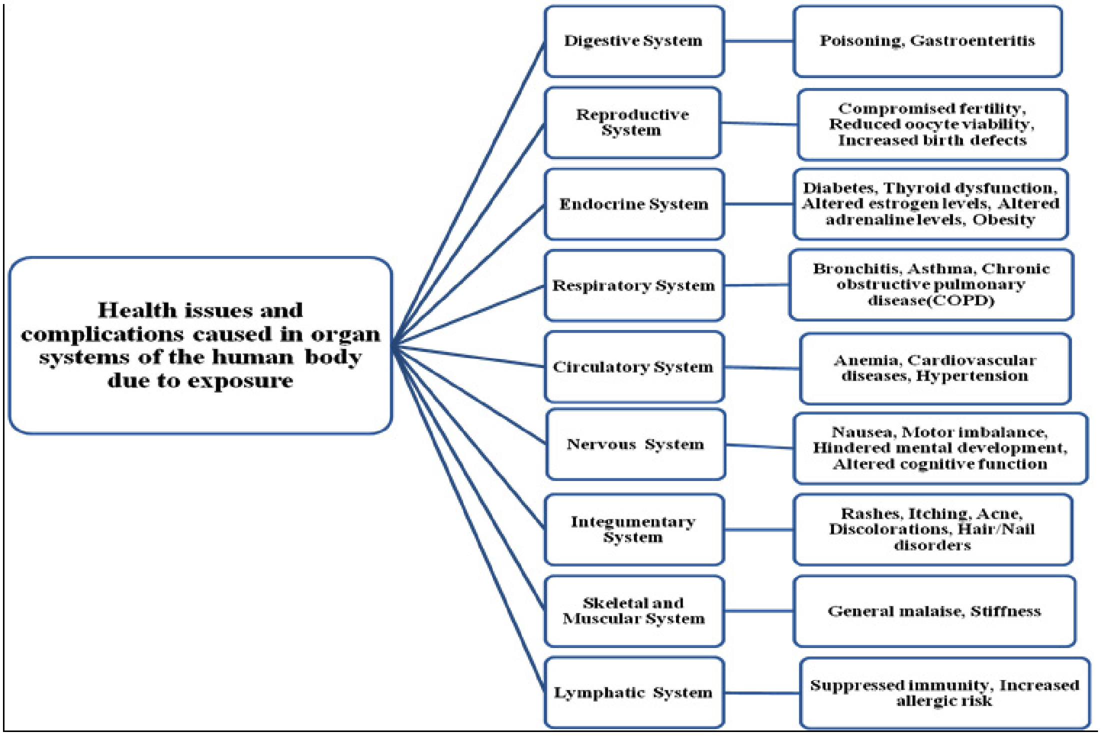

Fig. 2. Health issues and complications caused in various organ systems of the human body due to exposure to POPs

diseases. Immunotoxic effects include changes in immune cell function and antibody production. The liver is a major target organ for many POPs. Prolonged exposure can lead to hepatotoxicity, causing inflammation, fatty liver disease, and impairment of liver function. Some POPs have been linked to cardiovascular problems, including increased risk of heart disease and hypertension[30]. These effects may be related to the disruption of lipid metabolism and inflammation. Children exposed to POPs, especially during critical developmental stages, may experience delays in physical and cognitive development. Behavioral issues, such as attention deficits and hyperactivity, have also been associated with exposure to certain POPs.

POPs are likely to build up in the fat tissues of individuals and biomagnified as they move up the food chain. This can lead to higher concentrations of these pollutants in top predators, posing an increased risk to species at higher trophic levels, including humans[31]. Some POPs have genotoxic effects, meaning they can damage the genetic material in cells. This damage can lead to mutations, chromosomal abnormalities, and an increased risk of cancer. Efforts to mitigate the toxic effects of POPs involve international agreements such as the Stockholm Convention, which aims to eliminate or restrict the production and use of specific POPs. Additionally, regulatory measures, checking course, and public awareness campaigns are essential components of strategies to reduce exposure and protect both the environment and human health from the harmful effects of persistent organic pollutants. Recently, there has been considerable debate over the eco-toxicological consequences of POP on ecosystems, plant and animal life, and human well-being. As a result, numerous nations have banned or severely limited the use of POP. They are extremely persistent and hazardous because they are immune to practically all biological degradation activities. POPs not only have drastic consequences towards humans but also towards other animals, plants and environment[32].

Organic pollutants found in the ground, like fertilizers and pesticides, have caused an imbalance in the soil's microbiota's nutrition and plant growth. The harmful effects directly depend on the type of pollutant and the pH of the soil. The impact of persistent pollutants on enzymatic processes such as nitrification, ammonification, and cellulose degradation has been observed earlier[33]. A lot of pesticide runoff from agricultural areas along with production establishments' effluents, dyes, and POPs build up in waterways close by, causing a phenomenon known as bioaccumulation in living things. These, then enter various levels of the food chain and have a negative impact on both terrestrial and aquatic life[34]. POP-containing xenobiotics released by a variety of businesses and agricultural practices are not entirely eliminated from the ground, and POP-containing wastewater recycling causes them to become adsorbed into the soil. It has an impact on the number of microbes in the earth's soil, which damages plants and so disrupts the mutually beneficial interaction between plants and microbes. As a result, the functions of microbial biosynthetic processes are changed, which fully disrupts the cleanup of the contaminants and leads to slow breakdown. Additionally, it depletes nutrients of the soil, which impacts the productivity of crops as reported by earlier[35].

POPs have gained attention recently because of the hormonal imbalances they cause in humans and the abnormalities in endocrine and reproductive system functions they can cause in both humans and animals. In both humans and other animal species, these organic pollutants have the potential to cause malignancy, birth deformities, learning difficulties, immune-mediated, psychological, neural, and fertility issues.POP exposure causes immunosuppression, recurrent infections, developmental abnormalities, neurobehavioral impairment, cancer, and the formation or encouragement of tumors in neonates and children[36]. Long-term food exposure to some PAHs has been linked to skin carcinoma from skin contact, lung tumors from inhalation, and cancer of the stomach from ingestion[14]. Several POPs have been widely used for various purposes, and their effects on human health are well-documented. Here are some key POPs, their reported common uses, and their effects on human health discussed below (Table 2).

Methods for POPs Bioremediation

Several alternative techniques have been explored for the removal of POPs from the environment. These techniques aim to reduce or eliminate the presence of POPs in air, water, and soil. Phytoremediation involves the use of plants to extract, stabilize, or degrade pollutants. Certain plants have the ability to absorb and accumulate POPs from the soil, water, or air. Poplar trees and willows have been used for phytoremediation of soil contaminated with pesticides. Bioremediation utilizes microorganisms (bacteria, fungi) to break down or transform POPs into less harmful substances. Microbes can metabolize POPs as a carbon source for growth. Bacterial strains like *Pseudomonas* and *Bacillus* have been studied for their ability to degrade certain POPs. Activated carbon is known for its high surface area and adsorption capacity. It can be used to adsorb POPs from water and air. Activated carbon filters are commonly employed in water treatment to remove organic pollutants. Advanced Oxidation Processes involve the generation of highly reactive oxygen species to oxidize and break down POPs. This can be achieved through methods like ozone treatment, ultraviolet (UV) irradiation, and Fenton reactions. Ozone treatment has been used for the degradation of POPs in water treatment. Ozone (O_3) is a powerful oxidizing agent. Ozonation can be used to break down POPs into less harmful by-products and have been applied to the treatment of air and water contaminated with POPs. Sorbent materials, such as activated carbon, zeolites, and various polymers, can be used to adsorb and capture POPs from different media. Sorbent materials are often employed in the design of passive sampling devices for monitoring POPs in water. Soil washing involves the use of surfactants or chelating agents to extract POPs from contaminated soil, followed by separation and treatment of the washing solution. Surfactant-enhanced soil washing has been explored for the remediation of soil contaminated with organochlorine pesticides. Electro-kinetic processes use an electric field to transport POPs in the soil towards an electrode for subsequent removal. Electro-kinetic soil decontamination has been studied for the remediation of soils contaminated with chlorinated compounds. Green chemistry principles are applied to design processes that are environmentally benign which includes the use of eco-friendly solvents and methodologies for the removal or degradation of POPs. They may involve the use of non-toxic reagents and sustainable practices for the treatment of contaminated sites. These alternative techniques offer environmentally friendly and sustainable approaches for the remediation of areas contaminated with POPs. The effectiveness of each method can depend on the specific type of POP, environmental conditions, and the characteristics of the contaminated media. Ongoing research aims to improve the efficiency and applicability of these techniques for diverse environmental scenarios. To break down organic contaminants, three main methods are often employed: chemical, physical, and biological approaches. Chemical methods include Fenton's reaction, photo-Fenton, ozonation, sonolysis, photocatalysis, and electrochemical pathways[48]. Techniques including membrane filtration (nano- and ultrafiltration), granular activated carbon (GAC), coagulation, ion exchange, adsorption (powdered activated carbon (PAC), irradiation, osmosis, and reverse osmosis are among the evolving physical approaches[49]. Biosparging, bioventing, land farming, composting, slurry reactors, biostimulation, bioaugmentation and mycoremediation are among the techniques that are typically included in the biological approach[50] which involves bacteria, fungi, algae, and plants for the remediation of pollutants[51]. Microalgae-based technology stands out among these methods due to its single-step biodegradation process. Harvested microalgal biomass can also be converted into high-value biobased compounds, such as health supplements, biohydrogen, biohydrocarbons, and bioalcohols, to offset its production costs[52].

Microalgae Based Bioremediation

Microalgae are oxygen-evolving, photosynthetic microorganisms that resemble plants. They are found in a wide range of fresh and saltwater habitats as well as in wastewaters of all kinds, including those from cities, farms, industries, and other sources. Certain species can even thrive on plants, soils, rocks, etc. that contain sufficient levels of other necessary trace elements along with organic or inorganic carbon, ammonium, nitrate, urea, yeast extract, etc. and phosphorus[53]. They don't need fertile soil to develop because of their extremely low growth requirements and high adaptability, which allow them to be cultivated in a wide range of environmental circumstances[54]. Microalgae can finish a full development cycle in a few of hours with just sunlight, carbon dioxide, and basic nutrients like nitrogen, sulfur, and phosphorus. Microalgae are increasingly being used for a variety of biotechnological applications due to their low growth needs and the benefit of being used simultaneously for many technologies such as carbon reduction, biofuel production, and bioremediation [55].

Metabolic Diversity is one of the key aspects as microalgae exhibit a wide range of metabolic pathways, allowing them to metabolize diverse organic pollutants. This metabolic diversity makes them effective in breaking down complex chemical structures of POPs. Next is photosynthetic activity as microalgae harness solar energy through photosynthesis, converting it into chemical energy. This energy is utilized for the breakdown of organic pollutants, enhancing the efficiency of biodegradation processes. Then presence of variety of extracellular enzymes is another key feature. Microalgae secrete extracellular enzymes that play a crucial role in the degradation of complex organic compounds. These enzymes facilitate the conversion of POPs into simpler and more manageable by-products. Further, Microalgae have the ability to accumulate POPs within their cellular structures, a process known as bioaccumulation. This system lowers the concentration of contaminants in the aquatic environment while simultaneously helping to remove them from the water. As add on, synergistic interactions are often associated with them**.** Microalgae often coexist with bacteria in a symbiotic relationship. Some bacteria associated with microalgae possess the ability to further metabolize and degrade POPs, leading to a synergistic enhancement of the biodegradation process. The microalgae-based biodegradation approach offers several advantages over conventional methods, which includes chemical treatment or physical removal, including sustainability, cost-effectiveness, and minimal environmental impact. Moreover, it presents a potential solution for the remediation of water bodies contaminated with a variety of persistent organic pollutants. While this technology holds great promise, ongoing research is focused on optimizing the efficiency of microalgae-based biodegradation, understanding the interactions between different microalgal species and pollutants, and scaling up the process for practical applications in water treatment. Implementing this environmentally friendly strategy may contribute significantly to the restoration and protection of aquatic ecosystems, ensuring a sustainable and healthy water environment for future generations. Even at extremely low concentrations, they persist in the environment for extended periods of time. As the majority of POPs are fat-soluble, hence they get biomagnified after and migrate from lower to higher trophic levels in the food chain[56]. They can bio-accumulate in the fat tissues of organisms due to their lipophilic properties. POPs can also travel great distances by means of water and air over areas that are far from their original source of formation. They so become a matter of regional, national, and international concern. POPs have been detected in areas like the earth's poles where there is little human activity. This shows that POPs can even travel across areas with little to no assistance from humans[57]. Global warming and other climatic changes have a significant impact on the quantity of POPs present in the environment. POPs stored in soil and water bodies were released secondary to the planet's rising temperature[58]. Furthermore, POPs have been dispersed throughout many locations as a result of soil erosion brought on by seasonal events like floods and droughts. The distribution of POPs found in water bodies was similarly impacted by changes in water currents[57]. Halogen-containing POPs, a growing class of contaminants that cannot decompose naturally, showed greater resistance to biodegradation[59].

Due to their remarkable biological qualities, which include high photosynthetic efficiency, rapid reproduction rate, and simple structure, microalgae can grow under harsh environmental conditions like high salinity, the presence of heavy metals, nutrient stress, and extreme temperatures. They can also convert waste water nutrients into algal biomass[60]. A growing trend in the phycoremediation of harmful compounds is the use of microalgae because of their high binding affinity, abundance of binding sites, and wide surface area[61]. Moreover, microalgae's non-living biomass and living cells can both be used as biosorbents. Microalgae bioremediation of toxic compounds offers many advantages over higher plants, including exceptional removal capacity, environmental friendliness, robust and simple process, lack of toxicity constraint, rapid growth rate, and production of value-added products like biofuels and fertilizer. They play a crucial part in the self-cleansing of industrial, municipal, and agro-industrial wastewater because they can accumulate radioactive elements, organic and inorganic hazardous compounds, and both in their cells[62]. The analysis of the mechanics behind the microalgae-bacteria symbiosis system and comparing of modern sophisticated wastewater treatment systems with traditional ones was done earlier. Because of their mutually beneficial relationship, the microalgae-bacteria symbiosis system has the ability to remove POPs from a variety of sewage types. This technology is very helpful in fixing carbon dioxide and reducing carbon footprints. Applying microalgae-bacteria consortiums could reduce the cost and energy consumption in organic wastewater treatment compared to traditional wastewater processing because of their resistance to contaminants[63].

Selenastrum capricornutum, a microalga was tested for the degradation of o-cresol from wastewater. The results showed that *S. capricornutum* degraded o-cresol showing it had good degradation capacity for o-cresol[64]. Removal of a mixture with four veterinary antibiotics –tetracycline (TTC), ciprofloxacin (CPF), sulfadiazine (SDZ) and sulfamethoxazole (SMX)–in synthetic waste water using microalgae *Scenedesmus almeriensis* was studied. *S. almeriensis* removed tetracycline, ciproflaxin, sulfadiazine and sulfamethoxazole in descending order in synthetic wastewater[65]. *Chlorella vulgaris* and *Phaeodactylum tricornutum* were used to remove methylparaben (MPB) in another study. Degradation efficiency of MPB was higher in *C. vulagris* as compared to *P. tricornutum*as reported in previous studies[66].

Performance of microalgal photo bioreactor was tested for the removal, transformation and toxicity reduction of polycyclic aromatic hydrocarbons (PAHs) from wastewater[67]. The scientist found that microalgae removed PAHs which indicated that microalgae played significant important role in degrading organic pollutants in wastewater. *Chlorella vulgaris* was tested for biodegradation of different types of PAHs [2-ringnaphthalene (NAP), 3-ringanthracene (ANT) and 4-ringpyrene (PYR)].The three PAHs (NAP, ANT, and PYR in descending order) were all eliminated by *C. vulgaris* [68]as reported by Tomar *et al.,* (2022). For the purpose of efficiently breaking down tetracycline (CTC), a unique microalga-bacteria consortium was formed. The microalgae-bacteria consortium mostly used biosorption to remove and the adsorption capacity was found to increase in the presence of the microalgae-bacteria consortium[69].

Iohexol degradation by microalgae *Chlorella vulgaris* from sewage, surface water, and ground water was studied and it was seen that *C. vulgaris* removed half of the iohexol[70]. Lindane was used to establish bacterial, algal, and bacto-algal cultures in order to examine the breakdown and detoxifying capabilities of these organisms. After being treated with a bacteria-algal culture, lindane was effectively cracked[71]. Sulfamethazine (SMZ) biodegradation by plant-microalgal consortium and microalgal consortium was studied[72] as well for the treatment of emerging contaminants. A plant-microalgal combination was able to remove most of SMZ, but microalgae alone removed lesser of it. Additionally, ring cleavage, hydroxylation, and dehydroxylation by the intermediates contributed to the biodegradation of SMZ extracted after plant-microalgal remediation. In another trial, *Scenedesmus dimorphus* (Green microalgae), *Anabaena spiroides* (blue-green algae) and *Naviculapupula*(Diatoms) were used to degrade low and high density polythene. The selected microalgae multiplied greater on the low density polyethylene sheets than the high density polyethylene sheets after being biologically treated with their corresponding culture media. The treatment with *Anabaena spiroides* resulted in the highest percentage of degradation[73]. All these studies suggest that microalgae have immense potential as a bioremediating agent for POPs.

Bioremediation Mechanisms by Microalgae

The chief producers in aquatic bodies are algae, hence different algal species have evolved a range of detoxifying mechanisms to survive in water tainted with various forms of organic waste, incorporating biosorption, followed by bioaccumulation, biotransformation, biomineralization, and ex situ or/and in situ biodegradation. Consequently, it is thought to be the perfect biological material for fully using wastewater[74].

Bioadsorption: Adsorption is the process by which chemicals or ions physically bind to the surface of microalgae. The substance that has adsorbed at the interface is known as the adsorbate, and the algal surface that has allowed for adsorption is known as the adsorbent[75]. The process involves the distribution of soluble molecules and ions of organic pollutants between the liquid phase and the extracellular polymeric substances (EPS) or cell wall of microalgae. This distribution is caused by hydrophobic or ionic interactions between the pollutants and the solid surface of the microalgae, which the microalgae then release into their surrounding environments[76].

Bioaccumulation: Bioaccumulation, in contrast to bioadsorption, is a slower process that requires energy and is an active process. Microalgae have the ability to absorb and collect contaminants inside their cells for growth processes, in addition to nutrients. Pollutants can be accumulated by a variety of microalgae in opposition to the gradient in concentration between the cytoplasm and the external environment[77]. This process is described as having a central role in removing organic pollutants as it is a metabolic intracellular active pathway due to the binding of pollutants to intracellular proteins. Pollutant buildup has two possible effects: (i) it can cause reactive oxygen species (ROS) production, which balance cells and prevent damage or death; or (ii) it can accelerate the depletion of organic materials, suggesting that buildup is a prerequisite for biodegradation[78].

Biodegradation: Algae naturally break down organic materials into less complex compounds like carbon dioxide and water through a process known as biodegradation. Biological activities are primarily responsible for the transformation and breakdown of organic contaminants, which can occasionally lead to mineralization. Because they are naturally anaerobic and have an abundance of carbon and energy sources, aquatic sediments typically have a high microbial biomass and diversity, which may be able to break down organic contaminants[79]. The process of biodegradation depends on the metabolic activity of various enzymes present in microalgae such as hydrolase, phosphatase, phosphotriesterase, oxygenase, esterase, transferase, and oxidoreductase. The main enzymes involved in the biotransformation and detoxification of organic pollutants are believed to be esterase, transferase, and cytochrome P450. Other enzymes involved in the degradation process of organic pollutants include oxygenase, hydrolase, phosphotriesterase, oxidoreductases and phosphatase[80]. Enzyme metabolism is used in this multi-step process to break down organic pollutants. Chemical pesticides without functional groups can be made easier to dissolve, hydrophilic in nature and lesser toxic by using cytochrome P450 to stimulate them through oxidation, reduction, and hydroxylation procedures. Enzymes found in the cytosol move to organic contaminants that are activated or have functional groups that combine with glutathione, malonate, and glucose to produce conjugations. Glutathione transporters carry these conjugates inside vacuoles. However, the kind of pesticide and the microbial method play a major role in the biological degradation process of many organic contaminants[81].

CONCLUSION

Persistent organic pollutants (POPs) are so important to so many businesses that they can no longer be avoided in the environment. Because POPs pose a risk to humans, plants, and soil, it is imperative that dependable and efficient degradation processes be used to eliminate them and maintain the health of ecosystems. Various techniques have been employed for the degradation of these POPs but microalgae proved to be a promising tool for this purpose because of the presence of qualities like low production cost, high adaptability, can be grown in various extreme environments, and most importantly biomass can be converted to bio- based high value compounds. Microalgae are effective at removing POPs from various wastewater types, as demonstrated by reports and the available literature. This suggests that microalgae may be a viable option for the remediation of contaminated sites. In conclusion, the utilization of microalgae for the biodegradation of POPs in water represents a promising and sustainable approach to address environmental contamination. The unique metabolic capabilities of microalgae make them effective agents in breaking down a variety of POPs, contributing to the remediation of polluted water bodies. This eco-friendly strategy offers several advantages, including the potential for cost-effective large-scale applications, minimal ecological impact, and the generation of valuable biomass as a byproduct. The research and studies conducted in the field of microalgae-based biodegradation have provided valuable insights into the mechanisms underlying the degradation process, the selection of suitable microalgae strains, and the optimization of environmental conditions for enhanced pollutant removal. However, it is essential to continue advancing our understanding of the interactions between microalgae and different types of POPs to refine and optimize the biodegradation processes. Furthermore, the integration of microalgae-based biodegradation into existing water treatment systems and the development of scalable technologies are critical steps towards practical implementation. Collaborative efforts between researchers, industry stakeholders, and policymakers are necessary to bridge the gap between scientific knowledge and real-world applications. In summary, microalgae-based biodegradation of POPs holds great promise as a sustainable and effective solution for water remediation. Continued research, technological innovation, and collaborative initiatives will play key roles in unlocking the full potential of this environmentally friendly approach, contributing to the preservation and restoration of aquatic ecosystems worldwide.

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Conflict of Interest

The authors declare that there is not any conflict of interests regarding the publication of this manuscript.

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Data Availability

The information related to data will be made available on request.

Ethical Approval

None.

Author's contribution

Mamta Sharma: Performed the analysis and Manuscript preparation, Ameeta Sharma: Conceived study and designed the analysis, Neha Batra: Contributed data, Radhika Pareek: Manuscript preparation and collected the data and Sakshi Patel: Manuscript editing.

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