Chapter 16
Soils Contaminated with Persistent Organic Pollutants (POPs): Current Situations, Management, and Bioremediation Techniques: A Mexican Case Study

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Abstract The presence of different Persistent Organic Pollutants (POPs), such as organochlorine pesticides, polybrominated diphenyl ethers, polychlorinated aromatic compounds, polychlorinated dibenzofurans, polychlorinated dibenzo-*p*-dioxins, among others, has been reported in agricultural and industrial areas across different regions worldwide. POPs are highly toxic chemical compounds that cause severe adverse effects on ecosystems and have been related to multiple diseases in humans, including cancer, birth defects, and dysfunction in the immune, nervous, and reproductive systems. The Stockholm Convention is an international strategy for implementing policies to control or eliminate the production and use of these chemicals. In this context, developing strategies for the elimination and remediation of polluted sites by POPs is an urgent requirement. Bioremediation is a process

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whereby dangerous pollutants become less toxic or nontoxic moieties, reducing their concentrations to undetectable levels or eliminating organic pollutants using the physiological capabilities of living organisms. Therefore, bioremediation has been proposed as the most suitable biotechnology for the treatment of polluted environments with POPs. In practically all geographic regions of Mexico, different POPs have been reported in agricultural and urban areas. The main POPs reported include different organochlorine pesticides, such as aldrin, dichlorodiphenyltrichloroethane (DDT), endosulfan, endrin, and hexachlorocyclohexanes (HCHs), in agricultural districts, while in urban areas the most studied POPs were polychlorinated biphenyls and polybrominated diphenyl ethers. In Mexico, the scientific research in POPs bioremediation has been focused on identifying and characterizing microorganisms (bacteria and fungi) capable of biodegrading POPs as a bioprospection strategy for future bioremediation applications. In the present chapter, the chemical characteristics of POPs, their impact on ecosystems and human health, as well as the presence of these compounds in different localities of Mexico and biodegradation studies are reviewed.

Keywords Biodegradation · Dioxins · Environmental pollution; Pesticide · Polychlorinated compounds

16.1 Introduction

There are many organic chemical compounds, with high toxicity, whose generation and release into the environment are related to human activities. Therefore, it is necessary that they should be detected and quantified. Among pollutants, those that have attracted the most attention are those that do not degrade easily and are often the most toxic; these chemicals are recognized as POPs. POPs are a group of compounds of both natural and anthropogenic origins. However, through different industrial processes, human activities constitute the main cause of the intentionally and unintentionally POPs generation (Rottem 2017). POPs are harmful substances that pose a significant environmental and human health risk. POPs are diverse in chemical structure, however they share common characteristics, such as high environmental persistence due to their resistance to the natural biochemical, chemical, and photolytic degradation processes, and high toxicity to living organisms. POPs are semi-volatile compounds with a high capability of long-range transport to other places, such as the polar regions, they also can be bioaccumulated in the fatty tissues of animals, humans included (Rottem 2017; Wahlang 2018; Wang et al. 2019; Kim et al. 2020; Sun et al. 2020; Sheriff et al. 2021). POPs comprise a group of numerous artificial chemicals including dioxins, brominated flame retardants (BFRs), organochlorine pesticides (OCPs), perfluorinated compounds (PFCs), polychlorinated biphenyls (PCBs), and inclusively, polycyclic aromatic hydrocarbons (PAHs) (Wahlang 2018).

With the establishment of the Stockholm Convention in 2001, an international agreement to regulate the production, distribution, use, and disposal of POPs was reached (Sheriff et al. 2021). The first Stockholm Convention list of POPs included 12 priority pollutants: aldrin, chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, heptachlor, hexachlorobenzene, mirex, toxaphene, PCBs, polychlorinated dibenzo-*p*-dioxins (PCDD), and polychlorinated dibenzofurans (PCDFs); these chemicals were known as the "dirty dozen" (Tandon 2021). The production and extensive use of these chemical formulations began shortly after the end of World War II (Jennings and Li 2015). The Stockholm Convention bans these *"first generation"* 12 chemicals because of their toxicity, persistence, bioaccumulation, and long-range transport (Patel et al. 2021). Additionally, the Basel and Rotterdam Conventions contemplate hazardous wastes and other special wastes, such as medical and electronic waste; and provide an information exchange procedure for international trade, such as imports of pesticides and other dangerous substances, in an attempt to reduce the environmental and human health impacts (BRS Conventions 2021).

Many countries signed and ratified Stockholm Convention in 2003 and have subsequently developed their national implementation plans (NIPs). However, some of these countries have proved reluctant to ratify the language of the Convention. Derived from this, the proposal of new compounds and their inclusion in the Convention is complex. Such reluctance increases the production, use, and environmental release of compounds that threaten human health around the world. The signatory parts of the Stockholm Convention must take legislative and administrative actions to prevent the POPs associated environmental impacts, in both inside their territory and at the global level (Sharkey et al. 2020). However, the current knowledge state, environmental management practices, the degree of political and economic controversy in the POPs issue, as well as the importance of this topic in the public opinion and among policymakers, make it challenging to apply (Rottem 2017). Mexico has a robust legal framework that regulates POPs. In addition, numerous evaluations of sites contaminated with POPs have been carried out in different country regions, to establish the quality of the soil and water, highlighting the urgency of developing management alternatives and remediation strategies for these contaminated areas. On the other hand, POPs exposition monitoring studies have been performed in different regions of the Mexican territory to generate a profile on the POPs people exposure. In México, population exposure to DDT, a pesticide used in public health, as well as the exposition to PAHs derived from biomass combustion in indigenous communities has been documented. In addition, communities in industrial and urban areas are exposed to polybrominated diphenyl ethers (PBDEs) and the PCBs present in brick kiln smoke and non-controlled waste disposal sites (Orta-García et al. 2014).

In the present chapter information about the general characteristics of POPs, the sources, pollution, and other environmental impacts are reviewed. It also covers human health threats, POPs environmental biomonitoring and ecotoxicology, the International and Mexican regulation related to POPs, soils polluted by POPs in Mexico, the management alternatives of POPs in Mexico, as well as the bioremediation alternatives.

16.2 Persistent Organic Pollutants (POPs)

16.2.1 What Are POPs

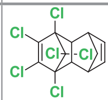
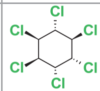
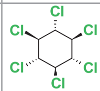
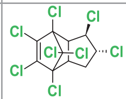
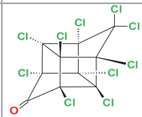
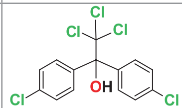
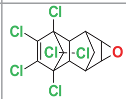
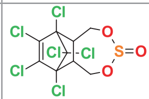
Persistent Organic Pollutants (POPs) are limited water solubility and highly toxic chemical compounds, broadly resistant to most of the physical, chemical, and biological degradation processes in the environment. Due to these characteristics, POPs can persist in nature for a long time in the different environmental strata and be mobilized through the soil, water, and air. In addition, the high lipid solubility of these chemicals lets them be bioaccumulated in animal and human tissues, as well as their biomagnification through the trophic webs (Fu et al. 2003; Klánová et al. 2009). According to their chemical characteristics, POPs are semi-volatile and low water solubility compounds, with molecular weights ranging from 200 to 500 Da (Jacob and Cherian 2013). These chemicals commonly are highly halogenated (Br, Cl, F), being chlorine, the main halogen element present in this group of compounds. The number of carbon–chlorine bonds in a POP compound is directly related to its persistence; the higher the number of these bonds, the more hydrolysis stability and degradation resistance is shown by the compound (Yarto et al. 2003; Weinberg 2009; Venegas and Naranjo 2010; Guo and Kannan 2015; Lorenzo et al. 2018; UNEP 2021).

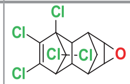
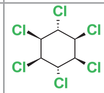
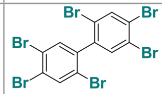
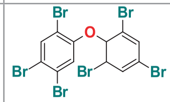
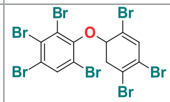
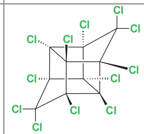
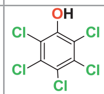
Different studies worldwide have evidenced the adverse environmental and human health impacts of POPs (Fu et al. 2003; Lorenzo et al. 2018). Therefore, the Stockholm Convention on Persistent Organic Pollutants, established in 2001, aims to protect the environment and human health from POPs. This international instrument requires governments to implement measures to eliminate, reduce the production, use, import, export, and environmental release of POPs (Weinberg 2009). In 1995, at the Stockholm Convention, an initial list of POPs that included 12 chemical compounds that were considered as priorities was created. The first included compounds were: aldrin, dieldrin, chlordane, DDT, endrin, heptachlor, hexachlorobenzene, PCBs, PCDD, PCDFs, mirex, and toxaphene (Yarto et al. 2003). In subsequent years, several novel chemicals were included in the Stockholm Convention list of POPs: Chlordecone, HCHs (α-, β-, and γ-isomers), hexabromobiphenyl, tetrabromodiphenyl ether and pentabromodiphenyl ether, hexabromodiphenyl ether and heptabromodiphenyl ether, perfluorooctane sulfonic acid, and perfluorooctanoic acid in the year 2009; endosulfan in 2010; hexabromocyclododecane in 2013; hexachlorobutadiene, pentachlorophenol, its salts and esters, and the polychlorinated naphthalenes in 2015; decabromodiphenyl ether and the short-chain chlorinated paraffins in 2017; and finally, dicofol and pentachlorobenzene in 2019 (UNEP 2011, 2021).

POPs have been classified in three general categories: (1) Pesticides used in agriculture, (2) Industrial chemical products used for diverse applications, and (3) Chemical products generated unintentionally because of incomplete combustion or chemical reactions (Weinberg 2009). Worldwide, pesticides have been employed for multiple activities, including pest control in agriculture, disease vectors control, among others. Once applied, pesticides are volatilized from crop fields to the atmosphere, or are translated to soil, superficial and underground water bodies through runoff and infiltration events. The presence of these pollutants in the environment favors their entrance to the organisms, where pesticides are bioaccumulated in their tissues. The release of pesticides included in the POPs list is implicated in several adverse impacts in the environment, as well as threats to the biodiversity and human health (Gaur et al. 2018). Among the POPs of group two, industrial chemical compounds, PCBs have been reported as highly dangerous to the environment and human health. These chemicals are broadly used for diverse industrial applications due to their unique characteristics of low inflammability, heat resistance, chemical stability, low vapor pressure, high boiling point (320–420 °C), and dielectric properties Due to their intensive use since the 1930s, pollution caused by PCBs has been registered in several regions around the world (Abou-Elwafa 2015; Vukasinovic et al. 2017; Dave et al. 2021).

Currently, 30 POPs are listed in the Stockholm Convention (UNEP 2021). The information related to these compounds is shown in Table 16.1. These POPs are classified in three annexes (A, B, and C). Chemical compounds in Annex A are subject to the prohibition of their production, use, importation, and exportation. The compounds listed in annex B are subject to restrictions in their production and use. However, some of these compounds have exemptions to these restrictions. For example, the use of the pesticide DDT is allowed for the control of disease vectors, such as the mosquitoes of the *Anopheles* genus that are the transmitters of the parasite *Plasmodium* sp. in Malaria, as well as the perfluorooctane sulfonic acid, which is a compound employed in the photographic industry, and the production of semiconductors, plates of metal, certain medical devices, firefighting foam, and insect traps. The compounds listed in Annex C include PCDDs and PCDFs whose unintentional release must be reduced. These compounds are produced and released into the atmosphere due to incomplete combustion and chemical reactions during open waste burning, fossil fuels combustion, and chemicals production processes (UNEP 2011; UNEP 2017; Gaur et al. 2018).

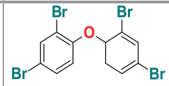
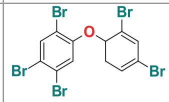
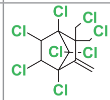
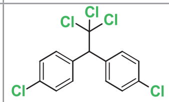
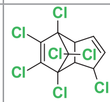
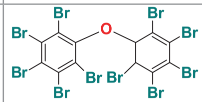
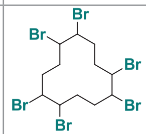
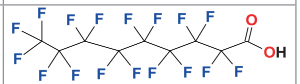
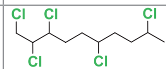
Table 16.1 POPs included in the Stockholm Convention (Fiedler et al. 2013; Jones 2021; UNEP 2021)

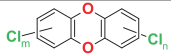
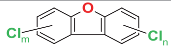
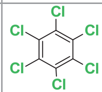
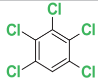
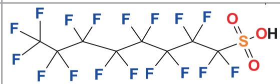
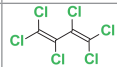
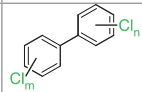
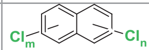
Category	POP name	Acronym	CAS number	Structure	Classification
Pesticide	Aldrin		309-00-2		Elimination
	α-hexachlorocyclohexane	α-HCH	319-84-6		
	β-hexachlorocyclohexane	β-HCH			
	Chlordane		5103-74-2		
	Chlordecone		143-50-0		
	Dicofol		115-32-2		
	Dieldrin		60-57-1		
	Endosulfan		115-29-7		

Category	POP name	Acronym	CAS number	Structure	Classification
	Endrin		72-20-8		
	γ-hexachlorocyclohexane	γ-HCH	58-89-9		
	Hexabromobiphenyl	HBB	36355-01-8		
	Hexabromodiphenyl ether	PBDE	68631-49-2 207122-15-4 446255-22-7		
	Heptabromodiphenyl ether		207122-16-5		
	Mirex		2385-85-5		
	Pentachlorophenol, its salts and esters	PCP	87-86-5 131-52-2 27735-64-4 3772-94-9 1825-21-4		

(continued)

Table 16.1 (continued)

Category	POP name	Acronym	CAS number	Structure	Classification
	Tetrabromodiphenyl ether	BDE	5436-43-1		
	Pentabromodiphenyl ether	PBDE	32534-81-9		
	Toxaphene		8001-35-2		
	Dichlorodiphenyltrichloroethane	DDT	50-29-3		Restriction
	Heptachlor		76-44-8		
Industrial	Decabromodiphenyl ether	Deca-BDE	1163-19-5		Elimination
	Hexabromocyclododecane	HBCD	25637-99-4		
	Perfluorooctanoic acid	PFOA	335-67-1		
	Short-chain chlorinated paraffins	SCCPs	85535-84-8		

Category	POP name	Acronym	CAS number	Structure	Classification
Unintentional production	Polychlorinated dibenzo-*p*-dioxins	PCDDs			Unintentional production
	Polychlorinated dibenzofurans	PCDFs			
Pesticide, industrial, and unintentional production	Hexachlorobenzene	HCB	118-74-1		Elimination and Unintentional production
	Pentachlorobenzene	PeCB	608-93-5		
Pesticide and Industrial	Perfluorooctane sulfonic acid	PFOS	1763-23-1		Restriction
Industrial and unintentional production	Hexachlorobutadiene	HCBD	87-68-3		Elimination and Unintentional production
	Polychlorinated biphenyls	PCBs	11097-69-1		
	Polychlorinated naphthalene	PCN			

16.2.2 Sources, Pollution, and Other Environmental Impacts

POPs as dibenzofurans and dioxins are generated naturally through volcanic activities and forest fires. However, human activities mainly produce these compounds through industrial processes, waste incineration plants, and agricultural activities (Gaur et al. 2018; Thakur and Pathania 2020; Akhtar et al. 2021). The environmental fate of the POPs is the atmosphere, which is the main transport media for these compounds (Fernández and Grimalt 2003). Next, these compounds can reach the water bodies, where they accumulate in the tissues of aquatic organisms (bioaccumulation) increasing their levels through trophic webs (biomagnification), generating adverse secondary effects (Lorenzo et al. 2018). POPs can also be found in soil and river sediments (Ren et al. 2018; Thakur and Pathania 2020).

POPs have generated significant adverse effects over a great diversity of species; their presence has been reported in almost all trophic levels, endangering the biodiversity of the polluted sites (Akhtar et al. 2021). Furthermore, the POPs exposition has been correlated with the reduction in the population levels of several species, due to immunotoxicity, failure in the function of the endocrine, reproductive and immunologic systems, as well as mortality increase in pups, deformations, increase in the incidence of tumors, thinning of the eggs wall, metabolic changes, cancer, changes in their behavior, alterations in the activity of the glutathione-S-transferase enzyme, as well as adult mortality, among others (Yarto et al. 2003; Venegas and Naranjo 2010; García et al. 2012; Alharbi et al. 2018). Likewise, POPs affect environmental factors such as temperature, precipitation, thaw, and biogeochemical cycles such as the carbon cycle, contributing to global warming (Thakur and Pathania 2020).

16.3 Human Health Threats

POPs generate serious problems for human health. Different authors, such as Alharbi et al. (2018), Zacharia (2019), Djangalina et al. (2020), and Thakur and Pathania (2020) point out that different POPs have been found in embryos, fetuses, and people of all ages. Human diseases related to POPs exposition include adverse effects on the endocrine system function, due to their profile as endocrine disruptors, generating hormonal alterations, adversely affecting the reproductive system resulting in birth defects, premature labor, developmental disorders, low birth weight, among others. POPs are also related to the development of cancer, cardiovascular diseases such as hypertension, angina pectoris, cardiac arrhythmias, among others, as well as to obesity, learning disabilities, diabetes, chloracne, porphyria, atherosclerosis, and neuropsychological impairment (Fig. 16.1). According to Tam et al. (2021), the World Health Organization reports 4.9 million deaths directly caused by POPs exposure each year, in addition to millions of people who develop POPs related diseases.

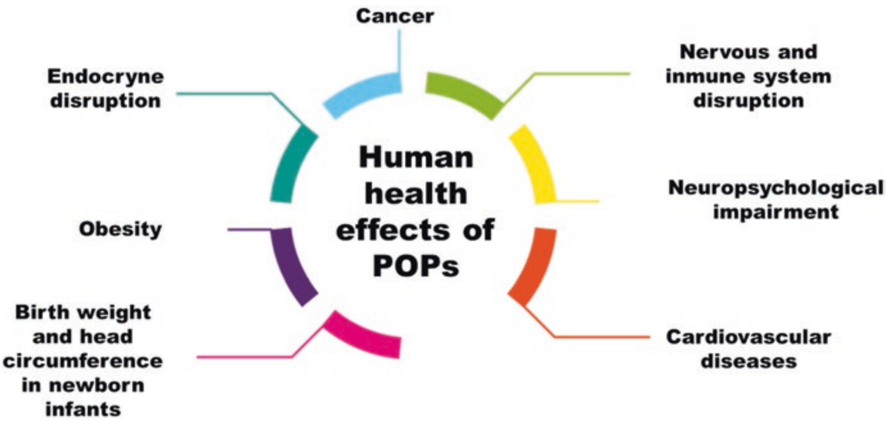


Fig. 16.1 Examples of human health problems related to POPs

16.4 POPs Environmental Biomonitoring and Ecotoxicology

Ecotoxicological studies evaluate the impact of toxic substances on the processes of natural ecosystems, as the flow of matter and energy of ecosystems, the dynamics of communities, the distribution and abundance of populations, and the morphology, physiology, and behavior of individuals (Galloway and Depledge 2001). There are some facts that need to be considered for biomonitoring and assessing ecotoxicological studies regarding the POPs environmental effects. (1) Since POPs bioaccumulate and biomagnificate along the food chain, these effects can be monitored at different levels of biological organization (from molecules to ecosystems). In ecotoxicological studies, biomarkers from the individual to the ecosystem level are used, considering the effects seen at the cellular and subcellular levels (Mussali-Galante et al. 2013). (2) These include a wide range of acute and chronic health effects, including cancer, congenital disabilities, immunosuppression, neurological disorders, and reproductive alterations. POPs are also referred to as endocrine disruptors (Kallenborn 2006; Mitra et al. 2011) being this last toxicity mechanism that is one of the most studied areas to date. (3) As endocrine disruptors, POPs directly compete with several natural hormones displacing them from their respective receptor binding sites, consequently, these pollutants are considered to act as synthetic hormones. The hormonal imbalances caused by pollutant-associated endocrine disruption have proved to be valuable indicators for documenting POPs adverse effects on various organisms (Kallenborn 2006). Hence, ecotoxicological studies and biomonitoring strategies should consider the use of biomarkers for assessing the ecotoxicity of POPs at various levels of the biological organization.

Currently, biomarkers give additional knowledge that cannot be obtained from the analysis of POPs concentrations alone. Also, they may incorporate the effects of chemical mixtures through a long exposure time. It is advisable to use a multibiomarker approach at different levels of the biological organization to evaluate the effects of POPs on the environment, in order to establish a more robust approach to any possible effects that may occur. At polluted sites, the organisms that integrate the top of the food web can bioaccumulate high POPs concentrations in their tissues, pollutant concentrations that exceed the individual toxicity thresholds, trigger several biochemical and physiological alterations in the exposed individuals. Therefore, ecotoxicological studies generate the bases for the prevention and reduction of risk by characterizing and evaluating the possible effects caused by the presence of toxic compounds and substances. In studies at the ecosystem level, it should be considered that toxic pollutants do not occur in isolation but in mixtures, or in combination with physical and biological agents.

Furthermore, in ecotoxicological surveys, the selection of a biomonitor species must be made according to the pollutant of interest and the site that needs to be monitored. The main suggested criteria for selecting them properly are (1) reduced mobility, (2) being in contact with the pollutant; (3) accumulation of high levels of the pollutant; (4) high abundance; (5) wide geographic distribution; (6) high longevity; (7) easy to sample; (8) easy to manipulate; (9) dose–response relationship; (10) long-term presence; (11) simple eating habits; (12) broad environmental stress tolerance; (13) well-defined species taxonomically; (14) extensive knowledge of its life history and biology (Haug et al. 1974; Phillips 1980; Phillips and Rainbow 1994; Rainbow 1995; Tanabe and Subramanian 2003; Luoma and Rainbow 2008; Zhou et al. 2008; Mussali-Galante et al. 2013). Associating molecular change to potential individuals, population, and community, with the aim of establishing links between the different levels of the biological organization is pertinent when considering the impact of POPs, because toxicity appears first in individuals before populations are affected, with subsequent changes at community level.

16.4.1 At the Individual Level

The effect of POPs will depend on the life stage of the exposed species, life history traits, overall health condition, and nutritional status. The main effects of POPs at the individual level are endocrine-disrupting, genotoxicity, ethology changes, reproductive alterations, immune dysfunction, and neurotoxicity.

Endocrine-disrupting. The consequences of these endocrine-disrupting effects can be observed mainly as physiological alterations in reproductive systems, specifically, alteration to sexual organs and hermaphroditism. The hormone-disrupting effects of anthropogenic pollutants have been shown to be valuable indicators for the documentation of pollutant effects on various organisms. For example, the induction of vitellogenin production (a hormone linked to egg production in females) in juvenile or male fish has become one of the most important biomarkers linked to endocrine-disrupting chemical agents. The relationship between POPs exposure and their effects using vitellogenin gene expression has been assessed as a biomarker of effects in fish (Zapata-Perez et al. 2007). For example, Zapata-Perez et al. (2007) studied the hardhead catfish (*Ariopsis felis*) from three ecosystems in the Southern Gulf of Mexico and Yucatan Peninsula. The authors detected that the concentrations of chlordanes, DDTs, HCHs, and PCBs were higher in exposed fish and that vitellogenin gene expression was over-expressed in fish collected from the site registering the highest levels of different POPs. Statistical analysis showed that the vitellogenin gene expression was significantly related to the concentrations of total DDTs and PCBs and negatively related to total Drins (dieldrin, aldrin, endrin).

Genotoxic damage. The genotoxic damage has been reported in different wild species exposed to POPs. González-Mille et al. (2019) found a significant association between total levels of POPs and genotoxic damage in different taxonomic groups, such as invertebrates, fishes, amphibians, and reptiles exposed to POPs mixtures. This is an important finding since genotoxic effects have been linked to ecological effects at higher levels of biological organization (Mussali-Galante et al. 2014).

Ethology changes. It has been documented that exposure to POPs (e.g., DDT) promotes alterations in the central nervous system, manifesting a deficit in learning and memory, and locomotion, as well as ethological alterations (Smith et al. 1976; Topinka et al. 1984; Tilson et al. 1987; Paul et al. 1994; Schantz and Widholm 2001; Mariussen and Fonnum 2006). In general, the main target of POPs (e.g., andrin, α-endosulfan, dieldrin, lindane, aldrin) in the central nervous system is the $GABA_A$ receptor (gamma-aminobutyric acid). Chronic exposure to POPs alters protein numbers, including antioxidant enzymes, receptors, and transporters of certain neurotransmitters, etc. (Slotkin and Seidler 2008, 2009). They also alter metabolic enzymes, including acetylcholinesterase, ion channels such as Mg^{2+}, Na^+/K^+ and Ca^{2+}, and ATPases of the plasma and mitochondrial membrane (Sahoo et al. 1999; Jia and Misra 2007), which contributes to changes in memory and learning. The brain accumulates large amounts of POPs comparable to adipose tissue. Therefore, brains exposed to levels of insecticides are capable of interfering with GABAergic neurotransmission (Vale et al. 2003).

Histopathological effects. As generated by POPs and a good effect biomarker that detects morphological alterations in various tissues by toxic agents. In fish exposed to chlordanes, dieldrin, DDT, and PAHs, histological liver abnormalities have been documented (Stehr et al. 1997).

Cancer. In addition to all the above-described effects at the individual level, many POPs are known or suspected carcinogens. PAHs, PCDD, and PCDFs are perhaps the most obvious examples (Jones and de Voogt 1999). Moreover, in top-predator species, POPs effects also extend to the immune system (Safe 1994; Ross et al. 1995), enhancing their susceptibility to disease and affecting their behavior patterns (De Swart et al. 1994).

Table 16.2 Sites in Mexico polluted with POPs

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
Northwest Region				
ΣCHL	0.38–0.72	Agricultural drain sediments	Mexicali valley, Baja California	Sánchez-Osorio et al. (2017)
ΣDDT	1.5–30			
ΣHCH	0.022–3.4			
ΣCHL	0.055–8.2	Residential soils		
ΣDDT	1.3–152			
ΣHCH	0.034–8.0			
DDD	0.84–12.4	Agricultural soils	Juarez Valley, Chihuahua	Núñez-Gastélum et al. (2019)
DDE	0.28–21.16			
DDT	0.13–171.86			
Endosulfan	0.75–1076			
Isodrin	0.71–17.07			
DDT	ND-336.2	Agricultural soil	Culiacan valley, Sinaloa	García-Hernández et al. (2021)
Endosulfan	1.4–1974.8			
HCH	ND-24.9			
DDT	0.51–21.95	Agricultural drain sediments	Culiacan valley, Sinaloa	García-de la Parra et al. (2012)
Endosulfan	0.5–4.85			
HCH	0.22–8.77			
PCBs	0.05–3.29			
Aldrin	ND-0.6	Agricultural and lagoon sediments	Navachiste-Macapule system, Sinaloa	Montes et al. (2012)
Dieldrin	0.2–2.5			
Endosulfan I	0.2–6.2			
Endosulfan II	0.2–2.5			
Endosulfan sulfate	0.7–9.4			
Endrin	0.3–27.0			
Endrin aldehyde	0.3–1.4			
Endrin ketone	0.3–9.8			
α-HCH	0.3–41.3			
β-HCH	0.3–533.3			
γ-HCH	0.3–7.7			
δ-HCH	0.3–70.2			
Heptachlor	ND–17.9			
Heptachlor epoxide	ND–0.6			
Methoxychlor	0.5–42.1			
p,p′-DDD	ND–0.6			
p,p′-DDE	0.4–2.8			
p,p′-DDT	ND–1.8			
DDT	ND–3131.4	Agricultural soil	Yaqui valley, Sonora	García-Hernández et al. (2021)
Endosulfan	ND–37			

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
CHL	0.009–1.0	Agricultural drain sediments	Yaqui valley, Sonora	Sánchez-Osorio et al. (2017)
DDT	0.21–55			
HCH	0.032–5.6			
CHL	0.062–25	Residential soils		
DDT	0.13–268			
HCH	0.035–3.1			
Aldrin	2.3	Agricultural soil	Caborca, Sonora	Leal et al. (2014)
α-Chlordane	1.2			
γ-Chlordane	2.4			
Dieldrin	3.3			
Endosulfan	8.9			
Endrin	5.6			
HCB	2.9			
α-HCH	2.0			
γ-HCH	1.4			
Heptachlor	2.73			
Isodrin	3.1			
Methoxychlor	2.4			
Mirex	2.2			
p,p′-DDD	3.1			
p,p′-DDE	9.6			
p,p′-DDT	1.3			
Aldrin	2.8	Agricultural soil	Hermosillo, Sonora	
α-Chlordane	2.6			
γ-Chlordane	2.0			
Dieldrin	2.3			
Endosulfan	3.6			
Endrin	7.5			
HCB	ND			
α-HCH	1.4			
γ-HCH	1.7			
Heptachlor	2.5			
Isodrin	8.4			
Methoxychlor	8.9			
Mirex	4.2			
p,p′-DDD	4.0			
p,p′-DDE	7.8			
p,p′-DDT	5.0			

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
Aldrin	2.2	Agricultural soil	Guaymas, Sonora	
α-Chlordane	2.3			
γ-Chlordane	3.8			
Dieldrin	4.3			
Endosulfan	3.9			
Endrin	19.0			
HCB	4.8			
α-HCH	3.7			
γ-HCH	2.0			
Heptachlor	3.4			
Isodrin	1.4			
Methoxychlor	3.1			
Mirex	1.7			
p,p′-DDD	1.8			
p,p′-DDE	45.8			
p,p′-DDT	4.2			
Aldrin	5.4	Agricultural soil	Magdalena, Sonora	
α-Chlordane	1.1			
γ-Chlordane	2.3			
Dieldrin	6.7			
Endosulfan	4.1			
Endrin	24.4			
HCB	0.7			
α-HCH	2.3			
γ-HCH	1.4			
Heptachlor	1.7			
Isodrin	0.4			
Methoxychlor	5.0			
Mirex	2.0			
p,p′-DDD	1.1			
p,p′-DDE	9.0			
p,p′-DDT	3.5			

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
Aldrin	1.0	Agricultural soil	Ures, Sonora	
α-Chlordane	1.7			
γ-Chlordane	1.7			
Dieldrin	0.9			
Endosulfan	1.4			
Endrin	18.8			
HCB	ND			
α-HCH	1.8			
γ-HCH	1.6			
Heptachlor	1.3			
Isodrin	ND			
Methoxychlor	4.2			
Mirex	1.5			
p,p′-DDD	1.1			
p,p′-DDE	1.0			
p,p′-DDT	0.6			
Aldrin	ND–41,000	Agricultural soils	Mayo valley, Sonora	Cantú-Soto et al. (2011)
BHC	ND–127,900			
Lindane	ND–3000			
Methoxychlor	ND–19,900			
p,p′-DDD	ND–23,200			
p,p′-DDE	ND–42,200			
p,p′-DDT	ND–120,400			
Aldrin	ND–74,000	Residential soils		
BHC	ND–938,500			
Endosulfan	ND–35,100			
Endrin	ND–161,400			
Lindane	ND–13,900			
Methoxychlor	ND–20,000			
p,p′-DDD	ND–39,300			
p,p′-DDE	ND–226,300			
p,p′-DDT	ND–301,200			

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
Aldrin	ND–15,900	Agricultural soils	Yaqui valley, Sonora	
BHC	ND–143,100			
Endosulfan	ND–124,000			
Endrin	ND–32,500			
Lindane	ND–2100			
Methoxychlor	ND–71,700			
p,p′-DDD	ND–13,300			
p,p′-DDE	ND–61,600			
p,p′-DDT	ND–110,000			
Aldrin	ND–25,800	Residential soils		
BHC	ND–292,400			
Endosulfan	ND–43,300			
Endrin	ND–377,300			
Methoxychlor	ND–19,700			
p,p′-DDD	ND–197,300			
p,p′-DDE	ND–621,300			
p,p′-DDT	ND–679,700			
Northeast Region				
DDT	25.3–790	Urban soil	Monterrey, Nuevo León	Orta-García et al. (2016)
PBDEs	1.80–127			
PCBs	4.0–65.5			
Western Region				
PBDEs	0.2–2.5	Lake sediments, urban	Chapala lake, Jalisco	Ontiveros-Cuadras et al. (2019)
PCBs	9–27			
PBDEs	0.3–1.5	Lake sediments, rural	El Tule lagoon, Jalisco	Ontiveros-Cuadras et al. (2014)
PCBs	1.7–24.7			
PBDEs	0.4–1.8		Santa Elena lake, Jalisco	
PCBs	1.5–15.4			
East Region				
Aldrin	9.31	Agricultural soil	Tepeaca, Puebla	Islas-García et al. (2015)
Endosulfan I	6.43			
Endosulfan II	1.91			
Endrín aldehyde	2.55			
Heptachlor	13.80			
p,p′-DDE	17.04			
trans-Chlordane	29.70			

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
HCB	0.2–1.5	Agricultural soil	Puebla and State of Mexico	Waliszewski et al. (2008)
α-HCH	0.2–2.2			
γ-HCH	1.0–7.2			
p,p′-DDE	2.0–7.1			
o,p′-DDT	4.9–31			
p,p′-DDT	22.9–99.2			
PCBs	0–88022.1	Agricultural soils	Tlaxcala, Tlaxcala	García-Nieto et al. (2019)
DDT	3.9–208.0			
PCBs	135–93,941	River sediments		
DDT	0.6–137			
PCBs	23.8–77	Lake sediments, urban	Las Matas lagoon, Veracruz	Ruiz-Fernández et al. (2012)
Midwest Region				
PBDEs	5–134	Urban soil	San Luis Potosí, San Luis Potosí	Perez-Vazquez et al. (2015)
PCB	ND–80.5			
DDD	ND–25.6			
DDT	ND–4.9			
Aldrin	0.65–1.35	Agricultural soil	Río Verde, San Luis Potosí	Velasco et al. (2014)
Endosulfan I	1.44–1.45			
Endosulfan II	0.27–48.62			
Endosulfan sulfate	1.96–9.51			
Endrin aldehyde	0.75–4.56			
α-HCH	0.58–0.92			
β-HCH	1.08–5.73			
γ-HCH	0.13–54.68			
δ-HCH	0.08–9.07			
Heptachlor	1.43–11.28			
Heptachlor epoxide	11.18–26.04			
Methoxychlor	1.20–37.70			
p,p′-DDD	1.04–19.32			
p,p′-DDE	0.13–15.01			
p,p′-DDT	14.9–144.10			
PBDEs	2.5–95.0	Urban soil	San Felipe Nuevo Mercurio, Mazapil, Zacatecas	Costilla-Salazar et al. (2011)

(continued)

Table 16.2 (continued)

POP	Concentration (ng/g DW)	Environmental sample	Location	Reference
South Central Region				
PCBs	253	Lake sediments, urban	Espejo de los Lirios, Mexico city	Piazza et al. (2009)
PCBs	621	Lake sediments, urban	Chalco lake, Mexico city	Piazza et al. (2008)
	63.7		Texcoco lake. Mexico city	
PBDEs	115–108,460	Urban soil	Alpuyeca, Xochitepec, Morelos	Perez-Maldonado et al. (2014)
Aldrin	0.1–12.2	Agricultural soil	Tlaltizapán, Morelos	Velasco et al. (2012)
Endosulfan I	0.1–16.2			
Endosulfan II	0.1–35.8			
Endosulfan sulfate	ND–17.9			
Endrin	0.2–18			
Endrin aldehyde	0.2–84			
α-HCH	0.2–129.6			
β-HCH	0.9–12.3			
γ-HCH	0.1–44.2			
δ-HCH	0.2–4.6			
Heptachlor	0.05–36.1			
Heptachlor epoxide	ND–11.1			
Methoxychlor	ND–34.4			
p,p′-DDD	0.2–25.6			
p,p′-DDE	0.1–70.6			
p,p′-DDT	0.2–79.1			
Southeast Region				
PCBs	6–372	Lake sediments, urban	Mecoacán lake, Tabasco	Armenta-Arteaga and Elizalde-González (2003)

DW Dry Weight, *ΣHCH* α-HCH + β-HCH + γ-HCH + δ-HCH (Hexachlorocyclohexanes), *ΣDDT* o,p′-DDE + o,p′-DDD + o,p′-DDT + p,p′-DDE + p,p′-DDD + p,p′-DDT, *ΣCHL* HEPT + HEPX + TC + CC (Chlordanes), *PBDEs* Polybrominated diphenyl ethers, *PCBs* Polychlorinated biphenyls, *ND* Non detected

Table 16.3 Methods applied in bioremediation

Strategies	Description
In situ bioremediation	
Bioaugmentation	Consist in the addition of pure of mixed exogenous microbial cultures to increase the microbial pollutants biodegradation
Bioventing	Consist in the injection of air to contaminated soil to stimulate microbial activity and pollutants biodegradation
Biosparging	Consist in the pressurized air injection below the contaminated water surface, oxygen supply stimulates microbial growth, aerobic biological activity and improve pollutants biodegradation
Biostimulation	Consist in the modification of the characteristics of the polluted environment to stimulate growth and biological activity of the microflora in charge of the bioremediation process; this includes the nutrients availability increase, adding sources of carbon, nitrogen, phosphorous, among others
Microbial assisted phytoremediation	Consist in the use of combination of plants and beneficial microorganisms for degradation and detoxification of pollutants in soil
Natural attenuation	Consist in the natural degradation of the pollutant by the biological action of the autochthonous microorganism from contaminated sites
Phytoremediation	Consist in the use of different higher plants species for soil remediation, plants can extract, stabilize, or biodegrade pollutants
Ex situ bioremediation	
Biofiltering	Consist in the use of a biofilter in which immobilized microorganisms retain or biodegrade pollutants
Biopiling	Consist in a bed of mound of contaminated soil, in which factors as moisture, temperature, nutrients, oxygen, and pH are controlled to enhance microbial pollutants biodegradation
Bioreactors	Consist in the use of a bioreactor system in which microorganism growing biodegrade pollutants. The system controls all parameter for supporting microbial growth and biological activity
Composting	Consist in the mixing of contaminated soil with a bulking agent, the pollutants are biodegraded by aerobic microbial and posterior thermophilic action using static or aerated piles in the treatment
Land farming	Consist in the treatment of contaminated soil, adding it to the superficial layer of the soil or into a treatment cell, polluted material is mixed periodically for biodegradation
Windrows	Consist in forming windrows of polluted soil, polluted material is rotated periodically for microbial-mediated degradation improvement

Sources: Das and Dash (2014); Azubuike et al. (2016); Sharma (2020); Raffa and Chiampo (2021)

16.4.2 At the Population Level

Effects of POPs exposure can be established between molecular and physiological alterations in individuals and changes at population level. These changes include:

Reduction in abundance of the population. It has been documented that wild population exposed to DDT and analogous insecticide rothane caused a reduction in population size. For example, fish-eating in the USA (Hunt and Bischoff 1960), birds of prey in Europe, North America (Hickey and Anderson 1968), and the UK (by a reduction in eggshell weight and thickness) (Ratcliffe 1967). These findings show the lethal effects and toxicity that POPs cause on top species of the food chain. Also, it has been documented that the insecticide dieldrin was responsible for the population crash of sparrowhawks (*Accipiter nisus*) in the UK (Sibly et al. 2000), demonstrating that high bioaccumulation of POPs found in the tissues of this predator species is clear evidence of the lethal effects of these pollutants.

Alteration in sexual organs. This effect can lead to low reproductive success and low fitness rates of the exposed population. Ecotoxicological research on wildlife populations has demonstrated that endocrine-disrupting chemicals profoundly impair animal reproduction and development. It has been documented that tributyltin (TBT) promotes masculinization in female marine mollusks, and this POP may cause a decline or local extinction of the population. For example, Bryan et al. (1986) and Gibbs and Bryan (1986) registered that the Dog whelk (*Nucella lapillus*) exposed to TBT decline its population size in the UK. The observed masculinization in females and the depressed reproductive capacity were explained by the competitive inhibition of TBT with cytochrome P450 dependent aromatase, enzyme responsible for the aromatization of testosterone and its conversion into estradiol (Matthiessen and Gibbs 1998). In many ecotoxicological studies, regional decline in fish, bird, and/or invertebrate populations resulting from exposure to POPs, such as DDT, PCBs, PCDD, and TBT has been related to biochemical, cellular, endocrine, and physiological effects in individuals (Vasseur and Cossu-Leguille 2006). One interesting finding is that organochlorines, notably DDED a metabolic breakdown product of DDT, can affect eggshell thickness in birds of prey (Ratclife 1967; Pearce et al. 1979), resulting in low fitness rates of the exposed population.

16.4.3 At the Community Level

In communities, particularly where contamination may act as a chemical stressor, different indexes and community properties have proved useful for evaluating the extent of environmental pollution. POPs can dissolve in the fatty tissues of organisms reducing their growth, size, fecundity, and fitness, which may eventually influence community structure (Arkoosh et al. 1998; Robinet and Feunteun 2002). However, few studies exist that evaluate changes in wild species assemblages (Clements and Rohr 2009). The little information generated so far at community level generates gaps in the effect of environmental pollutants on community structure, species composition, diversity, and functional groups. At community level, the most employed diversity measure indexes include the species richness, the Shannon–Wiener index (H′), and the Pielou evenness index (J).

In this context, in a study conducted by Neamtu et al. (2009) which characterized POPs in the Bahlui river in Rumania, the communities of phytoplankton and benthic invertebrates were monitored. They observed that water toxicity, related to the presence of POPs, appears to be higher for algae and less for benthic invertebrates, such as *Daphnia magna*, and indicated that primary producers reacted stronger than consumers at the presence of pollutants. The species richness in phytoplankton and macroinvertebrates appears to be negatively influenced by pollution. Also, the Shannon–Wiener diversity index, the Pielou evenness index, and the McNaughton dominant index each indicated that invertebrate communities appear to a have a more stable structure along the river. Johnston and Roberts (2009) documented, in a review and meta-analysis of the effects of contaminants on the richness and evenness of the marine community, that species richness is the most sensitive index for measuring community level effects, evidencing that polluted communities contain fewer species. Also, a near to 40% reduction in species richness was detected, regardless of the type of pollutants. It is important to note that as biological organization levels rise, the complexity of assessing cause-effect relationships between a certain pollutant and their effects also rises. That's why there are very few studies evaluating the ecotoxicological effects of POPs at higher levels of biological organizations, mainly at community level. Therefore, biomonitoring studies of ecological effects exerted by pollutants are urgent and necessary to gain information for more robust biomonitoring and mitigation strategies.

16.5 Soils Polluted by POPs in Mexico

According to Mexican normativity, a polluted site is defined as *"a place, space, soil, waterbody, installation or combination of these kinds of sites that has been in contact with materials or waste, which, due to their concentrations or characteristics, could represent a risk for human health, living organisms or the goods and properties of people*" (LGPGIR 2021). The causes of pollution are diverse. These include the inadequate disposal of different waste categories, leaks of hazardous materials or wastes from tanks, underground containers, tubes and ducts, the lixiviation of hazardous materials from places with production activities, storage sites, landfills, and dumpsites, as well as accidents and spills of chemical substances during transportation operations (SEMARNAT 2021).

The polluted sites can be divided into two main categories: those affected by environmental emergencies and the sites with the presence of environmental passives, the inadequate management of hazardous materials as well as the incidence of accidents that release toxic chemicals causes pollution in all environmental strata (soil, water, and air). The environmental presence and persistence of pollutants are recognized as a serious threat to ecosystems and human health. In Mexico more than 1000 polluted sites are registered. Contamination in these sites is related to different causes, including waste disposal, mining activities, industrial processes, and oil spills and its derivatives (SEMARNAT 2021). As pointed out above, the environmental presence of POPs is recognized as an important contamination concern worldwide. Mexico has committed to reduce POPs generation and encourage scientific research to identify and monitor sites polluted by these kinds of chemicals, as a signatory of the Stockholm Convention. Table 16.2 shows different studies carried out to detect and monitor the presence of POPs in environmental samples around Mexico. The country is divided into eight geographical regions (Northwest, Northeast, West, East, North Central, South Central, Southeast, and Southwest). In almost all regions' sites polluted by POPs have been detected.

Most of the 22 studies shown in Table 16.2 were carried out in the Northwest region, with seven studies carried out in Baja California, Chihuahua, Sinaloa, and Sonora. In these studies, the determination of the presence of different POPs in agricultural drain sediments, agricultural and residential soil, was achieved. The principal POPs monitored include OCPs such as DDT and its degradation products; lindane and other hexachlorocyclohexane isomers; aldrin, dieldrin, endrin, endosulfan, heptachlor, and methoxychlor (Cantú-Soto et al. 2011; García-de la Parra et al. 2012; Montes et al. 2012; Leal et al. 2014; Sánchez-Osorio et al. 2017; Núñez-Gastélum et al. 2019; García-Hernández et al. 2021).

In the South Central region of Mexico four studies have been carried out in lake sediments near urban areas of Mexico City (Piazza et al. 2008; Piazza et al. 2009). In addition, in agricultural and urban soils of the state of Morelos (Velasco et al. 2012; Pérez-Maldonado et al. 2014). POPs evaluated in these studies included polychlorinated biphenyl, PBDEs, and different OCPs.

In the East region, four studies have taken place, two of them evaluating OCPs in agricultural soil samples in the state of Puebla (Waliszewski et al. 2008; Islas-García et al. 2015). The study of García-Nieto et al. (2019) was focused on the evaluation of the presence of DDT and PCBs in agricultural soils and river sediments in the state of Tlaxcala, while in the state of Veracruz, the study carried out identified the presence of PCBs in sediments of the lagoon of Las Matas close to an urban area (Ruiz-Fernández et al. 2012).

In the Midwest region, three studies were identified, two of them for the state of San Luis Potosí. The first study was carried out in soil samples of urban areas to identify the presence of DDT, PBDEs, and PCBs (Perez-Vazquez et al. 2015), and the second evaluated the pollution caused by different OCPs in soil samples of agricultural areas (Velasco et al. 2014). In the same geographic region, Costilla-Salazar et al. (2011) evaluated the presence of PBDEs in soils of urban areas in the mining district of San Felipe Nuevo Mercurio in Mazapil, Zacatecas.

In the Western region, two studies looked at lake sediments of rural and urban areas of Jalisco and evaluated the presence of PBDEs and PCBs. Finally, just two studies were identified for both the Northeast and Southeast regions. Thus, in the city of Monterrey in the state of Nuevo León (Northeast region), the presence of DDT, PBDEs, and PCBs was evaluated in urban soil (Orta-García et al. 2016). While in the state of Tabasco (Southeast region), the presence of PCBs in the sediments of the Mecoacán lake was detected (Armenta-Arteaga and Elizalde-González 2003). For approximately 18 years, and according to the information shown in Table 16.2, several reports of the presence of POPs in agricultural and urban areas around Mexico have been published. Most of the studies have been carried out in soil and water bodies sediments near agricultural areas and urban zones. The presence of POPs evidences the negative impacts of human activities on the environment, especially those related to intensive agricultural and industrial activities.

Therefore, detecting and monitoring POPs studies are essential for establishing soil quality in urban and agricultural areas, highlighting the need for adequate management of these chemicals, and the urgency of developing feasible alternatives for the remediation of these polluted areas.

16.6 International and Mexican Regulation Related to POPs

At the international level different agreements have been signed related to chemical substances and hazardous waste, such as POPs. Among them is the Basel Convention, which covers hazardous waste and other wastes requiring special consideration, including medical waste, household waste, and electronic waste. Since January 1, 2021, it includes additional provisions for curbing the proliferation of plastic waste (BRS Conventions 2021). Furthermore, the Rotterdam Convention provides a structured information exchange procedure based on prior informed consent to international trade (the PIC Procedure), enabling parties to take informed decisions on future imports of hazardous pesticides and industrial chemicals, achieve good management, and lower the risk of harmful impacts on health and the environment. The Convention's implementation contributes to better production, a better environment, better nutrition, and a better life (BRS Conventions 2021).

In addition, the Stockholm Convention covering the elimination and reduction of POPs, such as PCBs and DDT, was adopted 20 years ago. The Convention was agreed in Stockholm, Sweden, in May 2001, and the date of entry into force was May 17, 2004, with 152 signatories (Rottem 2017; Stockholm Convention 2021). The objective of the Stockholm Convention is to protect the environment and human health from compounds recognized as POPs (Alshemmari 2021). The Convention is regulated by the United Nations Environment Program (UNEP) (Fiedler et al. 2019). This international Convention requires governments to follow up on the agreements established as well as the active participation of the organizations that are part of the International Network for the Elimination of POPs. Currently, 184 countries, including Mexico, have ratified the Convention (Sharkey et al. 2020).

The recently published third regional monitoring reports show that the concentrations of POPs in the environment and in human populations continue on a downward trend. The presence of POPs is ubiquitous but if measures are implemented to reduce or eliminate both intentional and unintentional releases, the concentrations measured in humans and in the environment will continue to decrease. The knowledge of the third regional monitoring reports also provides information on the monitoring of POPs and their relationship with changes in biodiversity and the climate change effects on the ecosystems function and structure (BRS Conventions 2021). Since 2005, Norway, Mexico, and the EU have assumed a leading role in nominating new substances for their inclusion in the Stockholm Convention (Rottem 2017). In 2005, five chemicals were proposed for their inclusion in the Convention, two by the EU, and three by Norway, Mexico, and Sweden, one by country. In 2006, five additional chemicals were proposed, three by the EU and two by Mexico. Finally, in 2009, at the fourth meeting of the Conference of the Parties were included nine of these ten nominated chemicals: (1) α-hexachlorocyclohexane, (2) β-hexachlorocyclohexane, (3) chlordecone, (4) hexabromobiphenyl, (5) hexabromodiphenyl ether and heptabromodiphenyl ether, (6) lindane, (7) pentachlorobenzene, (8) perfluorooctane sulfonate, and (9) tetrabromodiphenyl ether and pentabromodiphenyl ether (UNEP 2010a, 2010b; Selin 2010; Rottem 2017).

The three above-mentioned conventions constitute a coordinated life cycle approach to the environmentally good management of chemicals and waste across the world. The legally binding Basel, Rotterdam, and Stockholm (BRS) conventions share the common goal of protecting human health and the environment from the hazards of chemicals and waste, and have almost universal coverage with 188, 164, and 184 parties, respectively (BRS Conventions 2021). Mexico has made the decision to implement this international agreement through a National Implementation Plan (NIP), which was the product of a broad public consultation among authorities, industrial organizations, civil society organizations, and representatives of the private and academic sectors. In compliance with the commitments assumed by Mexico in the Stockholm Convention, the Mexican government has updated its NIP, and presented for registration with the Secretariat of the Convention in its 2016 version (INECC 2017; SEMARNAT 2017).

The legal framework for hazardous chemical substances and their waste provides many legal bases to regulate each step of their life cycle, from their manufacture or production to their final disposal as hazardous waste, which will greatly facilitate measuring the implementation of the Stockholm Convention. The Mexican Government has created numerous laws, regulations, and Official Mexican Standards (NOM) that together regulate every step of the life cycle of hazardous chemical substances and their waste, until their final disposal as hazardous waste (Romero et al. 2009). The instruments that make up the legal and institutional framework of Mexico related to POPs are made up of 17 national laws and 28 NOM, which fall under the responsibility of eight ministries of the 20 that make up the Federal Public Administration. However, the application of the legal provisions is complex due to the large number of legal systems that comprise it and the lack of coordination that has existed between the ministries for their creation, which has generated duplication of competences, regulatory gaps, and obsolescence of some of their instruments (Romero et al. 2009).

16.7 Management Alternatives of POPs in Mexico

In 2003, the General Law for the Prevention and Integral Waste Management (LGPGIR, acronym in Spanish) was issued as part of the Federal Constitution of Mexico to promote sustainable development, by preventing the generation, and promoting the recovery and integral management of waste, as well as preventing soil contamination (DOF 2003; Hernández-Padilla and Angles 2021).

This Law classifies waste as follows (DOF 2003):

(a) **Solid urban waste**. Those generated in homes, which result from the elimination of the materials used in domestic activities; the waste that comes from any other activity within establishments or on public roads that generates waste with domiciliary characteristics, and those resulting from the cleaning of public roads and places.
(b) **Special handling of waste:** These are generated during production processes, with characteristics not considered hazardous or solid urban waste. In addition, those are produced by large urban solid waste generators.
(c) **Hazardous waste:** Those that have any of the characteristics of corrosivity, reactivity, explosivity, toxicity, flammability, or that contain infectious agents, as well as containers, packaging and soils that have been contaminated when transferred to another site.

The LGPGIR established the obligation to formulate and implement management plans for hazardous waste, as well as, used, expired, withdrawn from trade or discarded products. Among them are persistent organic compounds such as PCBs, pesticides, and containers that still contain remnants thereof, which include those subjects to the Stockholm Convention. This law also establishes that hazardous waste generators must present Management Plans every year, which are environmental policy instruments that contribute to the improvement of waste management in Mexico. POPs are considered hazardous waste, so their management is established in the above-mentioned law. In Mexico, most of the products with POPs have been banned since 1994, especially pesticides. For this reason, to comply with the Stockholm Convention, attention is mainly focused on the substitution and elimination of the PCBs contained in electrical transformers and capacitors, as well as on the reduction or elimination of the release of dioxins, furans, and hexachlorobenzene in fixed and diffuse sources. Mexico, with the support of the North American Commission for Environmental Cooperation, and within the framework of the formulation of the National Action Plan, prepared a preliminary diagnosis of POPs. This diagnosis was made to establish the action plan for three groups of POPs: pesticides, industrial POPs, and unintentional POPs.

In the case of PCBs, it is estimated that Mexico imported between 6000 and 20,000 tons in total, which were mainly used in the electrical equipment of parastatal companies (such as the Federal Electricity Commission). For this, the Official Mexican Standard (NOM-133-SEMARNAT-2015, Environmental Protection-Polychlorinated Biphenyls (PCBs) -Management Specifications), was created. "*This Official Mexican Standard establishes the specifications for the environmentally adequate handling and disposal of hazardous waste that contains or is contaminated with PCBs when they are discharged, as well as for the handling and treatment of PCBs equipment*." This Official Mexican Standard, it is established that the handling of PCBs equipment, PCBs hazardous waste and PCBs liquid derived from maintenance activities, or due to removal of the equipment, must be managed through the following stages:

Table 16.4 POPs bioremediation studies in Mexico

POP	Microorganism	Concentration (mg/L)	Result in percentage	Reference
α-Endosulfan	*Bacillus subtilis*	14	76	Casanova et al. (2021)
	Bacillus pseudomycoides		95	
	Peribacillus simplex		95	
	Enterobacter cloacae		95	
	Achromobacter spanius		95	
	Pseudomonas putida		95	
β-Endosulfan	*Bacillus subtilis*	6	86	
	Bacillus pseudomycoides		86	
	Peribacillus simplex		86	
	Enterobacter cloacae		95	
	Achromobacter spanius		95	
	Pseudomonas putida		95	
Endosulfan lactone	*Soil microorganisms and Eisenia fetida*	0.001–0.009	90.1	Vázquez-Villegas et al. (2021)
DDT	*Lysinibacillus fusiformis*	50	41–48	García-de la Parra et al. (2012), Garcia et al. (2021)
	Bacillus mycoides			
	Bacillus pumilus			
	Bacillus cereus			
	Lysinibacillus fusiformis	200	26–31	
	Bacillus mycoides			
	Bacillus pumilus			
	Bacillus cereus			
α-Endosulfan	*Paecilomyces variotii*	17.5	26.4	Hernández-Ramos et al. (2019)
	Paecilomyces lilacinus		10.9	
	Sphingobacterium sp.		14.3	
β-Endosulfan	*Paecilomyces variotii*	7.5	31.4	
	Paecilomyces lilacinus		9.0	
	Sphingobacterium sp.		21.1	
α-Endosulfan	*Enterobacter cloacae* PMM16	1.7	71.3	Jimenez-Torres et al. (2016)
β-Endosulfan			100	
Pentachlorophenol	*Rhizopus oryzae* CDBB-H-1877	0.5	78.6	León-Santiesteban et al. (2016)
		2	90.8	

(continued)

Table 16.4 (continued)

POP	Microorganism	Concentration (mg/L)	Result in percentage	Reference
Lindane	*Streptomyces* sp. A5-M7	1.7	32.6	Fuentes et al. (2011)
	Streptomyces sp. A2-A5-M7-A11		33.1	
	Streptomyces sp. A2-A5-A8		31.4	
Pentachlorophenol	*Pseudomonas fluorescens*	200	77.6	Torres et al. (2010)
		400	94.5	
		600	94.1	
Aldrin	*Pseudomonas fluorescens*	10	94.8	Bandala et al. (2006)
Dieldrin			77.3	
Heptachlor			96.9	
DDT	*Pseudomonas fluorescens*	50	96.8	Santacruz et al. (2005)
		100	87.9	
		150	99.9	
Polychlorinated biphenyls (PCBs)	*Trametes versicolor*	600–3000	29–70	Ruiz-Aguilar et al. (2002)
	Phanerochaete chrysosporium		34–73	
	Lentinus edodes		0–33	
Pentachlorophenol	*Rhizopus nigricans*	12.5	100	Tomasini et al. (2001)
Pentachlorophenol	*Phanerochaete chrysosporium*	100	86	Mendoza-Cantú et al. (2000)

Storage. Hazardous waste of PCBs must be conditioned before being sent to the temporary storage of hazardous waste, considering the prevention of leachate generation and its infiltration into the soils; the dragging by rainwater or by the wind; fires, explosions, and accumulation of toxic vapors, leaks, or spills.

Transport. The transport of PCBs waste can only be carried out by land or sea. The carrier must be trained and have the necessary equipment and materials to contain spills that may occur during the transport of equipment and waste. Transport units that become contaminated by direct contact with PCBs liquids or PCBs hazardous waste must be subjected to cleaning activities, and the generated liquids and solids must be managed as hazardous waste.

Treatment and disposal. This must be carried out, in accordance with the following.

1. Washing of equipment with PCBs, and liquid–liquid extraction.
2. The liquid PCBs that are extracted from the equipment will have to undergo a process of elimination, through incineration, gasification, plasma, pyrolysis, and catalytic chemical.

3. In the case of spills to the soils with liquids containing PCBs, it is necessary to carry out a remediation process, considering the maximum permissible limits of contamination after the remediation. These limits range from 0.5 to 25 mg/kg, considering a subsequent agricultural, residential, and industrial land use, respectively. According to the soil characteristics and the conditions of contamination with PCBs, the biological, physical, or chemical treatments, or a combination of them, can be applied in this remediation process.

Also authorized is the installation of companies that provide transport, repackaging, shipping abroad for treatment (mainly by incineration), equipment decontamination, and chemical dechlorination of liquid waste. About the possibility of existence of generating sources of dioxins, furans, and hexachlorobenzene in Mexico, a diagnosis of the generation was carried out (2012). As a result, the total emission of dioxins and furans from the top ten sources were 9722 g TEQ/year, which include agricultural waste burning, cement kilns, forest fires, industrial waste incineration, medical/hospital waste incineration, metallurgical production, open dump fires, pulp, and paper mills, uncontrolled domestic waste burning, among others (SEMARNAT 2017). For the estimation of dioxin and furan emissions in Mexico, the emission factors provided by the Standard Instrument for the Identification and Quantification of Dioxin and Furan Releases (2005), for waste incineration equipment (hazardous, medical, municipal, etc.), were used (Costner 2005; UNEP 2005).

16.8 Bioremediation Alternatives of POPs

Bioremediation is a process that lets the biological degradation of dangerous pollutants to less toxic or nontoxic moieties, reducing their concentrations to undetectable levels, or eliminating organic pollutants using the physiological capabilities of living organisms (Ramírez-García et al. 2019; Vishwakarma et al. 2020). These organisms include bacteria, fungi, and plants, these the most reported microorganisms, both endogenous of the polluted sites to bioremediate or isolated from different environments and added to the site for the pollution treatment (Zouboulis et al. 2019). In addition, bioremediation has been proposed for the treatment of contamination derived from the presence of different pollutants in water and soil (Bharagava et al. 2020; Singh et al. 2020), including hydrocarbons (Xu et al. 2018; Ławniczak et al. 2020), pesticides (Giri et al. 2021; Sarker et al. 2021), and different persistent organic pollutants (Boudh et al. 2019; Devi 2020; Akhtar et al. 2021). In bioremediation, living organisms are the key factor involved in the biodegradation and elimination of pollutants. Due to this, adequate conditions for their development at the polluted sites are required for successful bioremediation, including adequate moisture, pH, temperature, oxygen, and the availability of nutrients. However, the presence of high-level salinity, metallic ions, and other toxic chemical compounds can reduce the effectiveness of the biological treatments (Khudhaier et al. 2020). These parameters can be controlled through the application of an adequate bioremediation strategy.

The bioremediation strategies are divided into two categories, in situ and ex situ technologies. In the in situ technologies, the polluted material bioremediation process is carried out at the contaminated site, while in the ex situ technologies, the biological treatment of the contaminated material is carried out in specific bioremediation installations (Das and Dash 2014; Azubuike et al. 2016; Sharma 2020; Raffa and Chiampo 2021). Examples of different bioremediation strategies are shown in Table 16.3. Several of these bioremediation strategies have been proposed as effective treatments for soil contamination caused by POPs, in different scientific studies which have been highlighted the potential of plants for POPs phytoremediation (Liu et al. 2018; Misra and Misra 2019; Futughe et al. 2020; Tripathi et al. 2020), as well as different microorganisms (bacteria, fungi, algae), exogenous or isolated from diverse polluted environments, capable of biodegrading POPs (Gaur et al. 2018; Boudh et al. 2019; Zacharia 2019; Mbachu et al. 2020; Sonune 2021).

In Mexico, different studies on POPs bioremediation have been reported in the last 20 years. In these studies, the potential of several microorganisms for application biodegradation and removal of different POPs have been highlighted. Table 16.4 shows 13 studies carried out in Mexico (2000–2021). These reports aimed to evaluate the biodegradation and removal of different POPs employing mainly bacterial and fungi strains. The research in the field of POPs bioremediation in Mexico has focused on the biodegradation of OCPs such as aldrin, DDT, dieldrin, endosulfan, heptachlor, lindane, and pentachlorophenol, with endosulfan being the most evaluated POP. In Table 16.4, just one study evaluates the fungal biodegradation of PCBs. All studies showed in Table 16.4 were carried out at laboratory scale, employing different in vitro approaches. Due to this it is important to evaluate these microorganisms in field studies on sites polluted by POPs. The main bacterial genus reported in the studies were *Bacillus*, *Pseudomonas,* and *Streptomyces*. With respect to the studies employing fungal strains the genus reported include *Lentinus*, *Phanerochaete*, *Trametes*, and *Rhizopus*. In Mexico, significant research efforts have been made to identify microorganisms, fungi, and bacteria, with great potential for applications in bioremediation strategies to eliminate POPs from contaminated sites. However, it is essential to carry out studies that include the evaluation of the biodegradation of other types of POPs, other than OCPs.

16.9 Conclusions and Future Perspectives

The semi-volatile, lipophilic, and high persistence characteristics of POPs were highlighted. These compounds have been detected in different world regions, even in places where they have never been used. Their impacts on the environment and health, on individuals, populations, and communities, have also been discussed, highlighting their toxicity and dangerousness when remaining in the environment. POPs waste can reach the soil, water, and air and remain for long periods. Studies to detect the presence of POPs have been carried out in soils from different regions of Mexico. Knowledge of polluted soils can help plan the restoration of these soils, make clear the need for adequate management, and the urgency of developing feasible alternatives for the remediation of these polluted areas. It has also been stated that Mexico has signed the Stockholm Convention, and to comply with that commitment it has developed internal legislation such as the LGPGIR (DOF 2003), NOM-133-SEMARNAT-2015 (DOF 2016), as well as the development of other instruments such as the Stockholm Convention Implementation, among others. In the LGPGIR, POPs waste is classified as hazardous, so there are standards that must be applied to POPs. For example, domestic legislation establishes how PCBs should be handled, which is why it is an activity monitored by the federal government.

In addition, bioremediation is an environmental-friendly and feasible method for eliminating and detoxifying pollutants, included POPs. Through bioremediation techniques such as phytoremediation and microbial-mediated pollutant degradation, the levels of POPs caused contamination can be reduced. Therefore, these bioremediation processes must be improved to offer a viable alternative for the degradation of POPs or the remediation of soils contaminated with the same compounds. It should be noted that Mexico is a country that has assumed the commitment to address the problem related to POPs, since it has established normative instruments for their management and treatment. In addition, economic resources have been allocated for the diagnosis of POPs in Mexico, for the analysis of soils, water, and air contaminated with POPs, as well as for the remediation of contaminated sites. However, much remains to be done. Greater investment is necessary for the development of technologies for its effective treatment, and for remediating sites contaminated with POPs. In this way, Mexico could have the necessary capacity to positively impact on the elimination of POPs.

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