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A comprehensive review on polychlorinated biphenyls in water, air and their impact on aquatic, terrestrial animals and humans

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Abstract

Polychlorinated biphenyls (PCBs) are human-made chemicals that were first introduced in 1929 for use as coolants and lubricants in electrical transformers and capacitors. Due to the severe environmental pollution and health problems caused by these chemicals, their production and use were banned in the 1970s. However, several studies have shown that despite this ban, PCBs continue to be produced unintentionally as byproducts of certain chemical reactions. Currently, the major sources of PCB production are chlorinated solvents used in chemical manufacturing, as well as in the production of paints and pigments. PCBs are highly persistent in the environment, as they do not easily degrade. As a result, they are still found in all environmental compartments, including surface water, groundwater, marine water, soil, sediments, air, and even in food items such as vegetables, fruits, dairy products, fish, and seafood. Notably, the concentration of PCBs in indoor air is significantly higher than in outdoor air. Humans and animals are exposed to PCBs through ingestion, inhalation, or dermal contact. Epidemiological studies have demonstrated that PCBs exposure and accumulation in the body can lead to serious health issues such as cardiovascular diseases, dementia, Parkinson's disease, immune system dysfunction, neuropsychological and neurobehavioral disorders, and disruption of endocrine gland functions. Moreover, PCBs can impair fertility and negatively impact the reproductive system, with some effects potentially being passed on to future generations.

This review aims to present the latest data on the concentrations of various PCB congeners in water, fruits, vegetables, fish, and seafood, and to examine their impacts on human health, animal well-being, and plant life.

Keywords: Polychlorinated biphenyls; Inhalation; Ingestion; Human; Animals; Plants

1. Introduction

Polychlorinated biphenyls (PCBs) (also known as chlorinated bi or diphenyls, chlorinated hydrocarbons, polychloro biphenyls) are composed of carbon, hydrogen, and chlorine atoms. PCBs can be synthesized by the chlorination of biphenyl in the presence of ferric chloride. These persistent anthropogenic organic compounds contain two benzene rings with the general molecular formula $C_{12}H_{10-n}Cl_n$ (where n = 1-10) [1]. In the literature, 209 congeners of PCB are reported. PCBs are semi-volatile and also exist in the vapor or particulate form. Although it was invented in 1876, it was first commercially used in the United States in 1929 as a coolant. As these congeners are non-polar, viscous, water-insoluble, chemically inert liquids with high dielectric properties and high temperature stability, they are used as heat exchange fluids, lubricants, and fire-resistant insulating fluids in electric transformers and capacitors [2]. Hydraulic fluids, heat exchange fluids, vacuum pump oils, de-dusting agents, inks, lubricants, waxes, carbonless copy paper and adhesives, sealants, fire retardants, cable insulating paper, flame-proofing, plastic and paint additives also contain one or more PCB congeners. These compounds not only persist for a long period but also travel great distances across international boundaries via air, water and migratory species, so are found in all the segments of the environment, viz.,

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air, water, soil, sediments, and food chain and have significant adverse impacts on the ecosystem, health of humans and animals [3-5].

In 1979, the USA banned its production because of its harmful effects on the population. A total international ban on the production of these chemicals came into effect on 17 May 2004. During the Stockholm Convention, the PCBs were included in the 'Dirty Dozen' pollutants. During the May 2001 session of the United Nations Environment Programme, it was decided that the PCB-containing products would be eliminated from the environment by 2028. Studies have estimated that approximately 17 million tons of PCBs remain in the environment [6]. Salvidge and Hosea [7] have reported that investigations have shown that PCBs are still produced as byproducts of several chemical reactions, denoting that several chemicals used otherwise contain a small amount of PCBs. Megson et al. [8] reported that, despite the ban imposed in 1979, approximately 43,000 tons of PCBs are still produced annually in the USA only as byproducts. These organic compounds in humans and animals are accumulated in fatty tissues and bio magnify in the food chain. Exposure to PCBs causes negative health impacts on humans and other animals. When humans are exposed to PCBs, it can disrupt hormone levels and adversely affect the endocrine, immune, and reproductive systems. PCB accumulation may also cause neurodegenerative diseases, diabetes, heart diseases, asthma, cognitive impairments, skin disorders, and cancer [9-11].

This review critically examines current studies measuring PCB levels in water, food, and air, and discusses major exposure pathways, their impact on human health, and aquatic and terrestrial systems. The results of this study will help policymakers and environmentalists to provide techniques to eliminate these toxicants from the environment

2. Sources of Polychlorinated biphenyls (PCBs)

Polychlorinated biphenyls are of anthropogenic origin. Major sources of PCBs include the combustion of coal, wood, oil, and diesel; emissions from the electrical equipment and paint industries; e-waste incineration; steel smelting; production and use of pesticides; disposal of fluorescent light ballasts; and certain building materials such as floor tiles, sealers and wildfires [12, 13]

2.1. Electrical equipment industry

Electrical equipment such as transformers, electromagnets, switches, voltage regulators, circuit breakers, and cables contains polychlorinated biphenyl compounds. The PCB congeners are also present in the transformers used in railcars and locomotives, air and gas compressor lubricants.

2.2. Scientific instruments

Polychlorinated biphenyls are present in instruments such as oscillatory birefringence, viscoelasticity, microscopy mounting fluid, optical liquids, and microscopic immersion oil that are used for scientific studies.

2.3. Natural gas pipelines

Natural gas compressors, scrubbers, filter and condensate contains PCBs.

2.4. Building material: Fireproof boards, panels used for doors, floors, ceilings, and partitions contain PCBs

Plasticizers: PCBs are used as plasticizers in PVC plastic, neoprene, chlorinated rubbers, sealants, and laminating adhesives. Epoxy resin, which has PCBs as a plasticizer, is used as a corrosion-resistant paint which, besides other things, is applied on navy ships [14]. PCB plasticized epoxy lacquer is used to coat plastic bottles so that they become resistant to aromas, acids, and alkalis. PCBs as plasticizers are also added to polyorganosiloxane, which is used in electrical coatings, insulating tapes, and protective lacquers. Electrical capacitors, ferrite computer magnet cores, and resistors have a coating of epoxy resin that has PCBs as a plasticizer.

2.5. E-waste recycling sites

In the developing countries, the developed countries dump e-waste, which, due to short life span and continuous updating of technology, is increasing [15,16]. Electronic equipment such as capacitors, ballasts, and X-ray machines contains PCBs. When this material is recycled, it releases PCBs in the environment [17-19].

2.6. Scrap metal recycling

Shredder waste, padding, insulation wires, upholstery of cars, oil and grease, insulated electrical cable, transformer scraps, and hydraulic equipment contain PCBs. When recycling PCBs, they are present with other pollutants and are released into the environment [20].

2.7. Other sources

Incineration of PCB-containing wastes emits PCBs into the air. Soil and groundwater near PCB manufacturing units and landfill sites are also contaminated with PCBs. PCBs are used in the manufacturing of carbonless copy paper; recycling these papers releases PCBs into the environment [21].

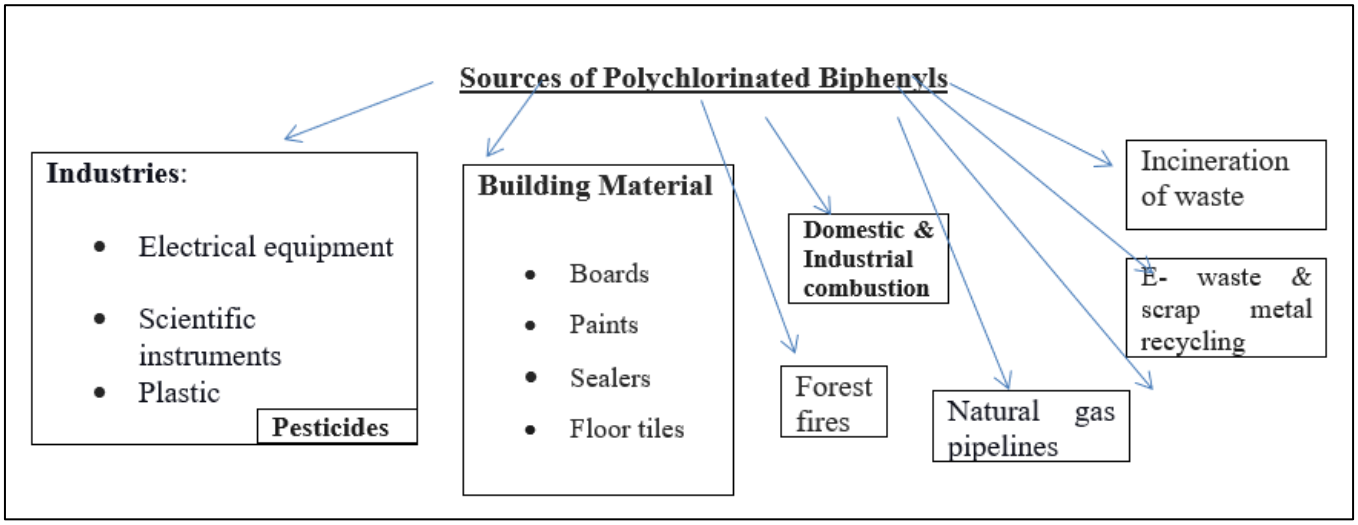


Figure 1 Sources of Polychlorinated biphenyls

3. Pathways of PCB entry in food Chain:

Polychlorinated Biphenyls (PCBs) are persistent, lipophilic compounds that accumulate in the fatty tissues of organisms. These toxic substances enter the food chain primarily through PCB-contaminated food sources. In aquatic systems, PCBs are introduced via industrial and domestic wastewater discharges, as well as atmospheric deposition. Once in water bodies, PCBs are bioaccumulated in aquatic organisms such as fish and seafood. Through the process of biomagnification, bigger fish accumulate higher concentrations of PCBs by consuming smaller contaminated fish.

In agricultural products, PCBs accumulate through contaminated soil, which can result from the irrigation with PCB-laden water, use of contaminated fertilizers or pesticides, atmospheric deposition, and leaching from improper PCB disposal sites. In dairy and meat products, PCBs enter the food chain when livestock consume contaminated feed, graze on polluted pastures, or drink PCB-contaminated water. Additionally, PCBs may infiltrate the food chain through food packaging materials that contain these harmful compounds. The concentration of polychlorinated biphenyls in water, air, dust, sediments and food materials is recorded in Table 1.

Table 1 The concentration of polychlorinated biphenyls in groundwater, surface water, Lake water, Sea water, River sediments, Marine sediments sewage water and food

Air	Ground water	Drinking/Surface water	Lake water / Canal water	River water	Sea water	Fish	Dust	River sediments	Lake/ Bay/sea sediments	Soil	sewage water/sludge	Food
1.54-35.75 ng m-3[22]; 12-194 pg m-3 (winter); 2.4-49pg m-3 (spring)[23]; 2000-5000pg m-3(industrial area) ; 5-30 pg m-3 (Residential) [24]; 450-726 pg m-3 (winter); 264-489 pg m-3 (spring); 262-412 pg m-3 (winter); 30-54 pg m-3 (spring) (outdoor)	6-67 ng/L[31] ; 0-29.8 ng/L[32]; 3.7-17.9 ng/L[33]; 5.2-169 ng/L[34]; 0.059-0.44 ng/L[35];0-560 ug/L[36]	3.8-167.1 pg/L[4]; 0.01-2.28 ug/L [18] ;22.59 ng/[37];0-56.25ug/L [36]; 0.15 - 5.21 ug/L [38];0.04-153g/L [39]	18.01-85.44 ug/L [40]; 0.26-0.34 ng/L[41] ; 72-834 pg/L[42]	0.04-11 ng/L [5];20-1860 ng/L[43]; 2.12-5.79 ng/L[44]; 0.065-1.92 ng/L [45];0.4-51.75 ng/L [16]; 0-4.5 mg/L[46]; 4.1-48n g/L [47]; 0.04-11.42 ng/L[48]; 0.6229-0.9358 ug/L[49]; 69.3-441ng/L [50];10.38 - 32.04ng/L [37];5.34-16.1 mg/L[51]; 0-34.8 ng/L [52]	0.29 ug/L [56]; 0.0028 - 0.0077 ng/L [57]; 20.48-422.32pg/L [2];6-32 ng/L[58] ;0-2ng/L[59]; 2.89-79.4 ng/L[60]; 4.1-48 ng /L [47]	0.17-2.68 ng/g (DW [61];64-425.4 ng/g [48] ; 15-35ng/g[58] ; 3.7-8.6ng/g [62];75 ng/g [63];200-300ng/g[64]	6.29ng/g [65]; 25473ng/g [26];11-1900 ng/g [66] ; 9.64-16.5 ng/g (Indoor); 3.48ng/g (Outdoor) [67];53.2-522.4 ng/g [68];168-5413ng/g [69]; 0.27-152.9 ng/g [70]	0.04-4.34 ng/g[71]; 0.0-63 ng/g [5]; 5.34-16.1 ng/g[43]; 0.0245-0.365 ng/g[57]; 5032-10132 ng/g [48]; 0.22-24.69ng/g [60];1621-2748 ug/kg [49] ;0.5285-5.869ng/g[52];0-18.33 ng/g [72]	.33-69 ng/g [5]; 0.55-3.29 ng/g(DW) [73]; 7.96-118.29 ug/g([40]; 1-3ng/g [58] ;0.4-0.9 ng/g [59]; 0.07-6.61 ng/g [60]; 4.3-64.3 ng/g [47]; 2-53 ng/g[74]	0-128.3 ng/g (0-20 cm depth); 0-137.6 ng/g (0-40 cm depth) [57]; 1-2.3 ug/kg (industrial);0.2 -0.4 ug/ kg (residential)[24];1.4-10.169ug/kg [33]	0.16-21.83ug/L [72] ;0-22.56 ug/L[75]; 66-752 ng/L [76];4.9-6.3ng/g [41]	Fish:0.581mg/kg[77];183.6-329.3pg/g[78];332.2 pg/g (canned fish)[78]; Meat: 84.7-288.2 pg/g[78]; 0-26.2ng/g fat [79];3.14 Ppb [80] Vegetables& Fruits: 33.39-10130pg/g[81]; 3.25-25.22 ug/kg[82]; 2.30-97ng/g; 2.71 - 151.67ng/g(grains)[83]; 0.46-1.17ppm[84] Dairy Products: 9.62-21.71ng/gfat[85]; 21.634(cream);12.317 ng/gfat (Icecream)[86]

; 306 pg m-3[25]; 2330ng/ m3 [26]; 25 pg/m3 [27]; 0.04-0.65 pg/ m3[28]; 1.18-10 pg/m3(ru ral area); 2.2 pg/ m3 (industria l); 3.11pg/m 3 (Urban) [29]; 5.3-81.14 pg/m3 [2];190-1100 pg/m3 [30]				;1.2-18.8 ng/L [53];24-27 ng/L[54]; 21.97-262.34 ng/L [55]								;267pg/g (butter)[77] ;56.3pg/g (cheese); 29.4pg/g (icecream)[78] Milk: (Breast milk) 0.01-0.03ppb [87];0.361-20.31 ng/g fat[88] ;1pg/g [78];8-250ng/gFat (Bovine milk)[89] Oil: Vegetable: 1.88-6.63 ng/L[90];66.9 pg/g [78]; Animal: 25.62ng/L[90] Other food; French fries: 14.1Pg/g; Pizza 26.6 pg/g[78] Poultrty:40.8pg/g[78]

4. Routes of exposure to humans and other mammals:

In the bodies of humans and other mammals, the toxicants, including PCBs, can enter by three ways, e.g., ingestion, inhalation, and dermal absorption.

4.1. Ingestion

Ingestion is the primary pathway through which polychlorinated biphenyls (PCBs) enter the bodies of mammals, including humans. The major dietary sources of PCB exposure include fish, other seafood, vegetables, fruits, meat, milk, and drinking water. Fish, particularly oily species such as salmon, sardines, fresh tuna, and swordfish, bioaccumulate PCBs from PCB-polluted water bodies. Fruits and vegetables absorb these toxicants through their roots from the soil that is contaminated with PCBs. The PCBs in dairy products and meat may be due to the ingestion of these pollutants by animals during grazing on contaminated grass or fodder. Children are additionally exposed to PCBs through breast milk and, in some cases, via transfer to fetal tissues during pregnancy. These persistent compounds in the human body accumulate in the bloodstream and various organs, primarily in the liver and pancreas.

4.2. Inhalation

Animals, including humans, inhale pollutants in the form of vapors, fumes, mists, aerosols, and fine dust. Polychlorinated biphenyls (PCBs) can enter the air and settle in dust due to the overheating of PCB-containing equipment, volatilization from waste sites during hot summer days, and incineration of contaminated waste. These toxicants then enter the bodies of animals and humans through respiration. During inhalation, PCB nanoparticles can reach the lungs and enter the bloodstream through the respiratory tract.

4.3. Dermal uptake

Since polychlorinated biphenyls (PCBs) are fat-soluble compounds, they can be absorbed through the skin upon contact with contaminated water, soil, or equipment. Dermal absorption is a significant exposure route, especially during the handling, repair, or maintenance of PCB-contaminated articles, as well as during disposal activities or accidental spills. Additionally, bathing or swimming in PCB-contaminated water can lead to the absorption of these toxic compounds through the skin. Dermal uptake is the main route of accumulation of PCBs in fish and other sea foods.

5. Effect of Polychlorinated biphenyls (PCBs) on the plant:

A Literature review indicates that uptake of polychlorinated biphenyls (PCBs) by plants mainly occurs via absorption by their roots from contaminated soil, and secondary through atmospheric deposition on shoots and leaves. Accumulation of PCBs in plant tissues has been shown to retard plant growth, reduce chlorophyll content, and decrease fresh plant weight [91-92]. The reduction in chlorophyll adversely affects the photosynthetic efficiency and energy production of plants, often leading to browning and stunted development of roots, shoots, and leaves. Furthermore, PCBs induce cellular damage by disrupting cell structure, compromising membrane stability, and affecting DNA structure and activity [93].Within plant systems, PCBs may also undergo biotransformation into hydroxylated derivatives (OH-PCBs), which are often more toxic than the parent compounds. Urbaniak et al. [94] reported that PCB accumulation in cucumber plants negatively affects various enzymatic activities, impairing physiological functions.

6. Effect of Polychlorinated biphenyls (PCBs) on aquatic animals:

Polychlorinated biphenyls (PCBs) in surface water, such as lakes, rivers, and ponds, not only deteriorate water quality but also disrupt aquatic equilibrium. These toxicants accumulate easily in the fatty tissues of aquatic animals and subsequently bio magnify through the food chain [95]. Umasangaji et al. [96], after their detailed studies, reported that approximately 40% of marine and freshwater organisms in Asia and Europe are adversely affected by PCBs.

PCB accumulation adversely affects animal health by altering enzymatic and hormonal functions in aquatic animal's body [97]. Growth and skeletal development of the animal is severely negatively impacted if the animal is exposed to PCBs at an early stage of life, while long-term accumulation weakens the immune system, increasing susceptibility to disease. According to Xiao et al. [98] and Zaynab et al. [99], PCB bioaccumulation in fish and other aquatic species adversely affects thyroid hormone levels, enzyme activity, blood parameters, behaviour, growth, skeletal structure, and reproduction, including eggshell thinning with abnormal development of the animal. In some fish and seafood species, PCBs also impair sensory organs.

Oxidative stress is another critical consequence of PCB accumulation, resulting from suppressed antioxidant enzyme activity. Singleman et al. [100], during their studies on Zebra fish, found that in zebra fish embryos, abnormal development of the heart, liver, pancreas, and blood vessels occurs in presence of PCBs. In the clam *Cyclina sinensis*, increased mortality, elevated oxidative stress, immune dysfunction, and disrupted energy metabolism in PCBs were observed by Klimova et al. [101] and Balbi et al. [102]

Liu et al. [103] reported that PCBs alter the activity of key antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GSH-Px) in fish and other seafood. Studies by Adzigbli et al. [104] and Sun et al.[105] further revealed that in molluscs, PCBs primarily affect the gills, hemolymph, and hepatopancreas. In the killer whales Megson et al. [106] found maximum 318 mg/kg lipid weight of PCBs, far exceeding the recommended limit of 9 mg/kg. They also reported that in major marine mammals, the concentration of PCBs exceeds the recommended limit, posing serious health problems and a significant risk to their life.

7. Effect of Polychlorinated biphenyls (PCBs) on terrestrial animals:

The literature survey reveals that terrestrial animals are adversely affected by exposure to polychlorinated biphenyls (PCBs). These toxicants negatively impact reproduction (e.g., reduced fertility), cause birth defects, impair overall health, and even threaten the survival of affected species [107,108]. In domestic pets, exposure to PCBs from indoor dust, contaminated food, and household products disrupts thyroid hormone function. Khidkhan et al. [109] observed a decrease in protein content, serum albumin levels, and testis weight in cats exposed to PCBs, along with increased lipogenesis following prolonged exposure.

PCBs have also been detected in birds. Studies have shown that accumulation of PCBs in avian species impacts developmental stages, alters fat content, and displays tissue-specific effects. Research in South Australia indicates that PCB exposure in animals leads to behavioral changes, impaired reproduction, weakened immune responses, anemia, and damage to the liver, stomach, and thyroid gland [110]. Long-term exposure may also result in liver and biliary tract cancer [111]. Takaguchi et al. [112] reported that PCB exposure through food, house dust, and other sources causes neurotoxicity in domestic animals. In high-yielding cows, exposure to PCBs not only deteriorates their health but also leads to contamination of their milk with elevated levels of PCBs [113]**.** Despite regulatory bans, PCBs continue to pose a serious threat to the survival and well-being of wild animals [113].

8. Impact of Polychlorinated biphenyls (PCBs) on humans

The uptake of polychlorinated biphenyls (PCBs) by humans is mainly through food (including vegetables, fruits, fish, dairy products, and seafood), water, and air. In the human body, PCBs initially accumulate in organs such as the liver, muscles, brain, and kidneys, and are subsequently stored in lipid-rich tissues like adipose tissue, breast milk, skin, and brain. The accumulation of PCBs in the human body adversely affects health. A literature review indicates that health impacts include various cancers, cardiovascular diseases, asthma, skin disorders, weakened immune function, cognitive impairments, and reproductive issues [114]. The severity of these health outcomes depends on factors such as the duration, frequency, and dose of exposure, as well as individual health conditions.

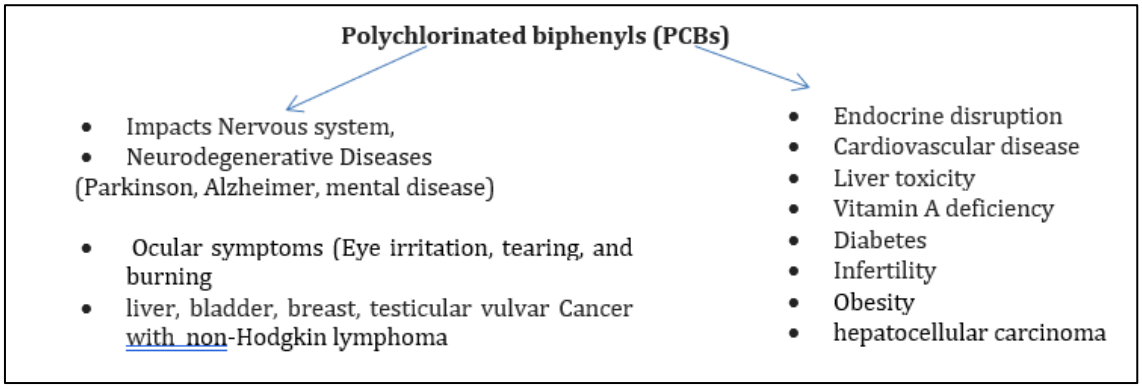
PCB accumulation in the human body induces liver toxicity by stimulating liver xenobiotic metabolizing enzymes such as aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphatase (AP), and lactate dehydrogenase (LDH), and gamma-glutamyl transpeptidase (GGT). This enzymatic activity leads to an increase in liver size due to proliferation of the endoplasmic reticulum, disrupting liver function and resulting in jaundice, nausea, vomiting, abdominal pain, anorexia, weight loss, and uroporphyria**.** In some cases, PCB accumulation has also been linked to hepatocellular carcinoma [115-117]. Exposure during prenatal development has been associated with autism spectrum disorders and behavioral problems in children [118]**.** There is also a significant positive correlation between PCB levels in serum and the incidence of neurological disorders such as dementia and Parkinson's disease [9,119]. Cardiovascular diseases, including hypertension and stroke, have been observed in epidemiological studies of PCB-exposed populations done by Raffetti et al. [120]. PCBs also suppress immune system function by reducing antibody production. Several studies [11,108,121] have reported PCBs as endocrine disruptors associated with diabetes, thyroid dysfunction (notably reduced T_3 and T_4 hormone levels), resulting in impaired memory, attentional process, and reproductive quality and fertility [122]**.** Stukenborg et al. [123] reported that PCB exposure leads to reduced semen quality, altered sperm concentration, and changes in reproductive hormone levels and gamete quality. Studies have also shown a correlation between PCB accumulation and testicular cancer [124,125].

Vitamin A, stored in the liver in ester form, is affected by PCBs through inhibition of the enzyme activity responsible for its storage, potentially leading to Vitamin A deficiency. Dermatological effects include chloracne, a persistent skin condition caused by dermal contact or ingestion of PCBs. Lesions are most common on the malar region, chin, and periorbital areas and may persist for decades.

Eye irritation, tearing, and burning (Ocular symptoms) have been reported following airborne PCB exposure by Cosentino et al. and Sendra et al [126,127]. Eyelid swelling, Meibomian gland hyper secretion, and conjunctival pigmentation were reported on long-term exposure by Moustardas et al. [128] and Segars et al. [129]. Increased PCB accumulation has been positively correlated with waist circumference [38], indicating a possible link to obesity. PCB accumulation significantly raises the risk of gastrointestinal and respiratory cancers [130]. Prolonged exposure is also associated with elevated incidences of liver, bladder, vulvar, and breast cancers, as well as non-Hodgkin lymphoma [9,131,132]

9. Conclusion

Despite the production of polychlorinated biphenyls (PCBs) being banned nearly fifty years ago due to their harmful effects on the environment, plants, aquatic life, and humans, these toxic compounds persist in food, water, and air. Recent scientific studies regarding the routes of release of PCBs in the environment are given in this review article. Humans and other mammals are exposed to PCBs primarily through inhalation, ingestion, and dermal contact. Due to their lipophilic nature PCBs bio accumulate in the fatty tissues of animals and humans and bio magnify through the food chain. Indoor air often contains higher concentrations of PCBs than outdoor air, and inhalation of such contaminated air especially by children leads to increased blood PCB levels. Once accumulated, PCBs persist in the body for extended periods. The severity of toxicity depends on the duration of exposure, the dose, the exposure pathway, the host's health condition, and age. According to the literature, PCBs act as endocrine disruptors and are linked to a range of health issues, including diabetes, obesity, skin diseases, weakened immune and nervous systems, and neurodegenerative disorders such as Parkinson's and Alzheimer's disease. They also contribute to cardiovascular diseases, ocular symptoms, and vitamin A deficiency. Moreover, PCB exposure is associated with liver toxicity, enzyme induction, genotoxicity, infertility, and reproductive disorders. Several types of cancers have been linked to PCBs, including liver, bladder, breast, testicular, vulvar cancers, and non-Hodgkin lymphoma.



Compliance with ethical standards

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Disclosure of conflict of interest

There is no conflict of interest.

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