

Multiple Environmental Sources of Exposure to Polychlorinated Biphenyls (PCBs): Relative Contributions and Health Risks—A Global Systematic Review and Scientometric Analysis

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Abstract

Introduction: This systematic review aimed to identify studies that simultaneously examined more than one source of exposure to polychlorinated biphenyls (PCBs) and evaluated the contribution of each source and associated health risks.

Methods: This study was conducted in compliance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. A comprehensive literature search was performed in the Scopus, Web of Science, and PubMed databases using predefined key terms up to March 21, 2024. Two reviewers independently assessed titles, abstracts, keywords, and full texts, and resolved disagreements by consulting a third reviewer. We assessed the methodological quality of the included studies using the modified Newcastle-Ottawa Scale (NOS). The CiteSpace 6.3.R1 software was used to visualize co-citation and keyword co-occurrence networks related to our research topic.

Results: A total of 2,123 records were initially identified, and after screening and eligibility assessment, 11 eligible articles met the inclusion criteria. Of these, all studies examined sources of exposure through food and air, whereas sources of exposure through drinking water and soil were evaluated less frequently. The numbers and types of PCB congeners varied substantially across studies, ranging from 6 to 205. Dietary intake was the most frequently reported contributor to PCB exposure. Only four studies conducted quantitative health risk assessments, reporting variable carcinogenic and non-carcinogenic risks depending on exposure source and population characteristics. Visualizing the software results revealed that dietary intake, persistent organic pollutants, dioxin-like PCBs, and risk assessment are the active and emerging research themes in this field.

Conclusion: Overall, available evidence suggests that dietary exposure remains the major contributor to PCB intake in the general population; however, evidence on the simultaneous contributions of multiple exposure pathways and their associated health risks remains limited world wide. Future large-scale, standardized studies are needed to comprehensively evaluate all major PCB exposure routes and improve global health risk assessment frameworks.

Keywords: Systematic review, polychlorinated biphenyls, PCBs, Contribution, Exposure, Risk assessment

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Introduction

Polychlorinated biphenyls (PCBs) constitute a group of synthetic, persistent, and toxic compounds consisting of a biphenyl structure containing between one and ten chlorine atoms (1,2). They were mostly used as plasticizers, dielectric insulating oils, lubricants in transformers and

capacitors, paints, and plastics (3,4). Moreover, the PCB group encompasses 209 congeners (different chemical compounds), all of which are lipophilic (1,2). This property increases with the number of chlorine atoms in their chemical structure; therefore, lower-chlorinated congeners are more volatile (e.g., PCBs 28 and 52), whereas highly



chlorinated congeners are less volatile and more lipophilic (1). Consequently, these compounds can bioaccumulate in the environment, the human body, and biota (5). Because of their structural characteristics, PCBs are categorized into non-dioxin-like (Ndl-PCBs) and dioxin-like (dl-PCBs) groups (exhibiting toxicological activity comparable to that of dioxins), which consist of 12 and 197 congeners, respectively (5,6). However, under the Stockholm Convention, the production of these compounds was banned for all members (7).

Air, food, water, and soil have been identified as routes of human exposure to PCBs (8,9). Dietary exposure has been reported to account for over 90% of total PCB intake in the general population (1,6,9). PCBs have been documented in numerous food categories globally. Fat-rich foods such as fish, dairy products, and meat constitute a major pathway of PCB intake in human populations (10–14). However, contradictions have been observed for other exposure routes. For example, some studies have indicated that inhalation exposure may be comparable to dietary exposure in certain environmental contexts (10,15) or higher than previously assumed (10,16). Additionally, although drinking water is generally considered a negligible source of PCB exposure (1), some researchers have still studied it and calculated its contribution to PCB exposure (17,18).

In addition, exposure to PCBs has been linked to a wide range of adverse health outcomes, including carcinogenic and non-carcinogenic, immunological, neurological, and endocrine effects (1,2). The International Agency for Research on Cancer (IARC) classified PCBs as Group 2A, meaning they are “probably carcinogenic to humans” (1,3).

Several epidemiological investigations have assessed these detrimental effects. Some of them were on diabetes and PCBs as endocrine-disrupting chemicals (EDCs) (19–22), and some of them were conducted on other diseases like hypertension and blood pressure (23–26), autism spectrum disorder (27–29), hepatocarcinogenesis (30), thyroid cancer (31), and dementia and Parkinson’s disease (32).

Furthermore, many studies have assessed the health risks of PCB exposure among different populations and age groups worldwide (4,33,34). Nevertheless, because each PCB congener has distinct physicochemical properties and may affect human health differently, applying these findings to assess human health risk remains challenging (35). Some countries use the tolerable daily intake (TDI) to assess PCB exposure and support health risk management. Germany, for example, proposed a TDI of 1–3 micrograms per kilogram of body weight for PCBs (1). Exposure to dioxin-like PCBs can also be estimated using toxic equivalency factors (TEFs), with overall toxicity expressed as toxic equivalents (TEQ) units. Overall, the daily intake of dioxin-like PCBs is estimated to represent approximately 10–30 percent of total TDI values expressed in TEQ units (1).

Given the importance of understanding PCB exposure patterns among individuals in a community and their associated health risks, it is necessary to identify exposure

sources, potential routes, and relative contributions of PCB exposures. Although a recent review by Weitekamp et al. (2021) examined polychlorinated biphenyl exposure routes and their relative contributions (10), the present study employed a hybrid approach combining systematic review and scientometric analysis to identify and synthesize studies that simultaneously evaluated more than one PCB exposure source, quantified their relative contributions, and examined associated health risk assessment.

Materials and Methods

Research question

This systematic review was conducted in compliance with PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (36). The structured research question was:

“What evidence exists regarding multiple environmental sources of PCB exposure, their relative contributions, and associated health risks?”

Search strategy

After determining the research question, we developed our extensive and systematic search strategy to find all suitable and relevant studies by using these keywords controlled with Medical Subject Headings (MeSH) as described below:

((“Polychlorinated Biphenyls” OR “PCBs” OR “Biphenyls Polychlorinated” OR “Compounds Polychlorobiphenyl” OR “Polychlorobiphenyl Compounds”) AND (“Origin of exposure” OR “Source of exposure” OR “Inhalation” OR “Dietary” OR “Dermal”) AND (“Contribution” OR “Share” OR “Portion” OR “Proportion” OR “Quota” OR “Allotment” OR “Segment” OR “Stock” OR “Section” OR “Distribution” OR “Sector”) AND (“Food” OR “Water” OR “Soil” OR “Air”)).

A comprehensive literature search was performed in the Scopus, Web of Science, and PubMed databases up to March 21, 2024. Furthermore, the reference lists of the included studies were manually reviewed to retrieve additional potentially relevant articles.

Eligibility criteria and data extraction

Subsequently, all articles were entered into the Mendeley reference manager, and duplicate articles were automatically removed both automatically (by the software) and manually (by the researchers). Afterward, we specified the necessary criteria for including and excluding studies as follows:

We included studies that quantitatively evaluated at least two PCB exposure pathways simultaneously (e.g., drinking water, food, soil, and air) and reported concentration, intake, or contribution data for human exposure assessment. We also included only articles published in English, but we did not impose any time limitation. Exclusion criteria included review articles, conference and seminar proceedings, letters to the editor, books, and studies on animal feed, seawater, street soil, and coastal sediments. We also excluded studies that focused exclusively on a single environmental matrix or lacked sufficient quantitative exposure information. Two researchers performed these steps independently

by evaluating the “Title,” “Abstract,” and “Keywords”; if they disagreed on an article, a third investigator evaluated it. Next, to assess the quality of the relevant articles, we prepared a data extraction checklist as follows:

Does the article evaluate at least two sources of exposure to PCBs? Does the article comprise any data about the PCB concentrations (minimum/maximum, or average)? Does it include information on the types and numbers of samples, as well as the sampling locations? Does the article report the number of measured PCB congeners? Are the measurement method and the reported unit correct for PCBs? When full-text articles were not accessible, we screened abstracts to assess whether they contained the required information as previously defined.

Additionally, the methodological quality of the included studies was assessed using the modified Newcastle-Ottawa Scale (NOS) critical appraisal tools appropriate for cross-sectional studies. Two reviewers independently assessed study quality and resolved disagreements by consulting a third reviewer. The maximum attainable score in the NOS depends on the version used. In this study, the maximum achievable score was 7 points. Following the percentage-based quality classification approach proposed for adapted versions of the NOS (37), studies were stratified into three categories: high quality (>75% of the maximum attainable score; 6–7 points), moderate quality (>50% to 75%; 4–5 points), and low quality (≤50%; 0–3 points). To evaluate the reliability of the initial study selection process, both reviewers independently evaluated a randomly selected sample of 100 articles. The results demonstrated a 99% agreement rate in study classification, with a Cohen’s kappa coefficient (κ) of 0.66, indicating substantial inter-reviewer agreement (38).

After reviewing the articles, we entered the extracted data into an Excel file. The extracted data included study location, year of study, sample size, exposure sources (food, water, soil, and air), type of PCB congeners, PCB concentrations (maximum/minimum, or average), exposed populations or community, the largest reported contribution of exposure sources, and health risk assessment findings.

Data time trend and analysis

To provide complementary evidence beyond the systematic review, we adopted a hybrid review approach integrating systematic review and scientometric analysis. We conducted scientometric analysis using CiteSpace 6.3.R1 software (39), a Java-based tool for scientometric and social network analyses. The same search strategy used for the systematic review was independently applied to the Web of Science Core Collection on April 1, 2024 (Supplementary A). All records retrieved from this search were exported and used as the scientometric dataset. Co-citation networks and keyword co-occurrence maps were visualized to identify major research themes and emerging research trends (40).

Results

Overview of included studies

The PRISMA flow diagram (Figure 1) presents all steps

of searching, screening, eligibility assessment, and article inclusion. Overall, this systematic review initially identified 2,123 articles, including 864 from Scopus, 977 from Web of Science, and 282 from PubMed. Additionally, four articles were identified through a review of other sources and the reference lists of relevant full-text articles. After removing duplicate records ($n=606$), the remaining studies were screened by title, abstract, and keywords; 1,401 records were excluded for irrelevance to the study objectives. Furthermore, we excluded review articles ($n=49$), books and book chapters ($n=13$), conference publications ($n=3$), and non-English articles ($n=3$) according to the predefined eligibility criteria. At the full-text screening stage, 52 articles were assessed for eligibility. Of these, 29 articles were excluded due to irrelevant study objectives, and 12 were excluded for methodological and quality-related concerns, including evaluation of a single exposure source or insufficient quantitative PCB data. Finally, 11 eligible studies met the predefined inclusion criteria and were included in the systematic review. As shown in Table 1, three studies have been conducted in the United States (15,41,42), two studies in China (43,44), and one in the United Kingdom (45), Japan (17), Pakistan (46), France (18), Turkey & Peru (47), and Nigeria (48).

In addition, all included studies were of moderate to high methodological quality according to the modified Newcastle–Ottawa Scale (NOS) (Table S1). The scores ranged from 4 to 7 out of 7. Seven studies were classified as high quality (≥ 6), demonstrating strong exposure assessment using validated analytical techniques such as GC-MS and standardized QA/QC procedures. Some of these studies also applied robust statistical approaches, including Monte Carlo simulations, multivariate comparisons, and spatial exposure analysis. The four remaining studies were rated as moderate quality (4–5), mainly because they adjusted for confounding factors only to a limited extent, although they maintained strong analytical validity (Table S2).

PCB concentration and exposure routes

Almost all included studies examined dietary exposure pathways, except Esen et al. (2023) (47) and Adesina (2021) (48). Similarly, ten studies evaluated air exposure (15,17,41–48), whereas drinking water and soil/dust exposure pathways were assessed less frequently – three (17,18,45) and six (17,43,44,46–48) studies, respectively. Only one study simultaneously examined four exposure sources, including drinking water, food, air, and soil (17), and the rest examined two or three sources of exposure. The food items studied differed across the included papers. Some studies had used the food baskets of other studies, which generally included a variety of foods (18,41,42). Others sampled the food items themselves; for example, in Pakistan, only two food items (rice and wheat) have been studied (46).

Overall, almost all studies in this review reported PCB concentration or daily intake. However, direct comparisons between studies were challenging because they used

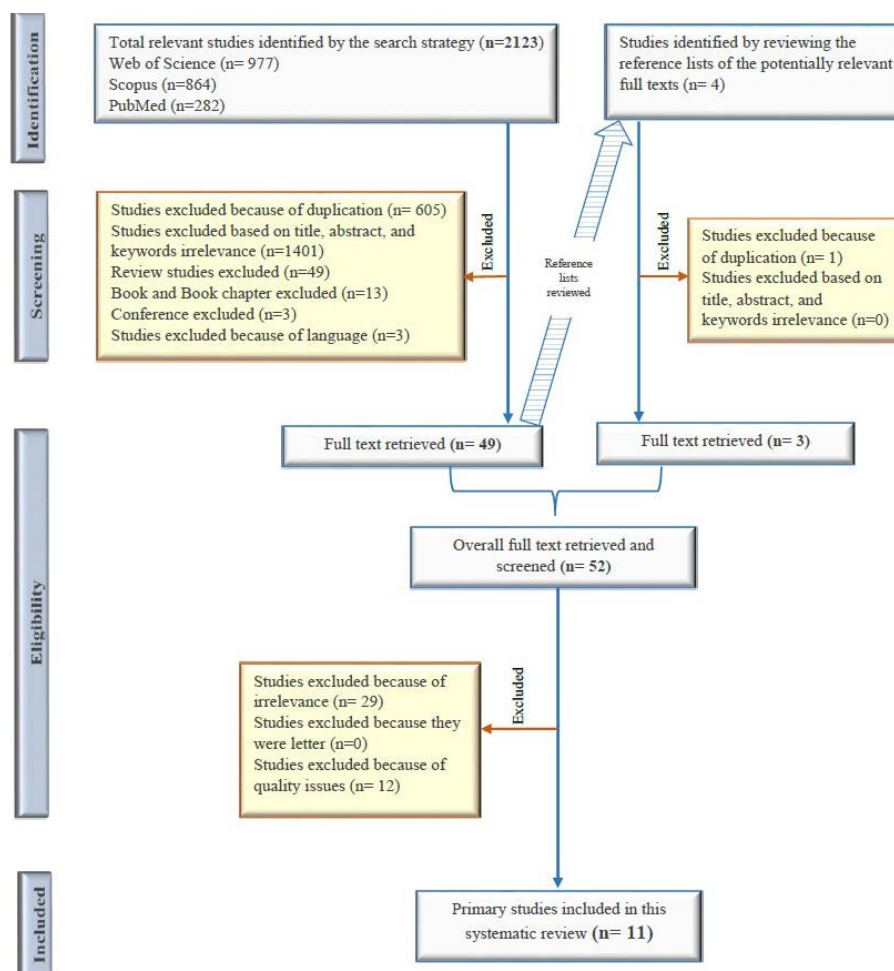


Figure 1. The PRISMA flow diagram of the study

different units of measurement. This inconsistency mainly stemmed from different analytical methods, target congeners, lipid-adjusted concentrations, TEQ-based measurements, and exposure assessment approaches.

Contribution of PCB exposure sources

Approximately 70% of the included articles (eight studies) (15,17,18,41–45) reported diet as the main source of PCB exposure. In the United Kingdom population, foodstuffs accounted for 98.8% of total PCBs-TEQ intake, with meat, dairy products & milk, and fish representing the largest dietary contributors (45). Similarly, in Japan, dietary exposure contributed more than 90% of total PCB intake, and fish and shellfish were the dominant contributors (17). Saktrakulkla et al. (2020) also reported that meat, dairy products, fish, and other dietary sources were the major contributors to PCB exposure in the United States (15).

Health risk assessment

Health risk assessment, as a worthy topic, was addressed in only four studies included in this review (43,46–48) (Table S1). They performed risk assessment through food, air (inhalation), and accidental ingestion of contaminated soil or dust. For example, the calculated hazard ratio index (HR) showed that the risk of rice is higher than that of wheat for the Pakistani population (46). Additionally, the hazard index (HI) associated with egg and fish

consumption indicated potential non-carcinogenic effects among exposed populations in China (43). This issue was not addressed in the other seven articles in this review (Table S2).

Time trends and patterns of the study

Figure 2 presents the major keyword clusters generated by CiteSpace, revealing the evolution and persistence of major research themes related to PCB exposure. CiteSpace identified 18 clusters, representing the intellectual structure and temporal development of research in this field. CiteSpace automatically assigned the cluster labels. Among the identified clusters, the largest were diphenyl ether (#0), dietary intake (#1), persistent organic pollutant (#2), dioxin-like PCB (#3), and organochlorine pesticide (#4), indicating that these topics have constituted the core research areas throughout the study period. Moreover, clusters #12 (migrating European silver), #13 (western basin), and #16 (risk assessment) have become more active in recent years, indicating emerging research interests in ecological monitoring, regional environmental evaluation, and human and ecological risk assessments.

The time-zone view and keyword co-occurrence networks (Figures 3 and 4) also visualized the issue's position and importance. Figure 3 presents the time-zone visualization of the keywords, illustrating the temporal evolution of research topics related to PCB exposure

Table 1. Characterization of the included studies in this systematic review

Reference	Year	Place of Sampling	Kind of measured PCBs	Source of exposure	Type of sample	Sample size	Exposed community	Concentration (measurement unit)	The largest contribution of exposure for ΣPCBs
Lv Y-Z et al. (43)	January to October 2020	Shijiao and Longtang Towns, Qingyuan City, China	24 PCB congeners	Air	Indoor air		People residing in e-waste recycling sites in China.	660 ± 530 pg/m ³	Among residents following a 100-foot diet and consuming locally caught wild fish, fish consumption was identified as the primary contributor to PCB exposure. In contrast, among residents who rely on commercially available foods, dermal absorption was the primary exposure pathway for most PCB congeners.
					Outdoor air			200 ± 98 pg/m ³	
				Food	Produced in the e-waste sites: Egg Fish Vegetable			(min–max, median) 8.2–94, 20 4.0–110, 18 0.22–7.7, 0.40	
					Produced outside of the e-waste sites: Egg Fish Roast goose/duck Raw chicken Raw pork			(min–max, median) 0.018–0.11, 0.086 0.09–0.44, 0.17 0.02–0.15, 0.05 0.07–0.25, 0.12 n.d.–0.03, 0.02	
					Dust	Indoor dust samples			
		Outdoor dust samples		35 ng/g					
Zhang B et al. (44)	November, 2020	Jiangsu Province in eastern China	12 dioxin-like PCBs	Air	Ambient air samples of 20 exposed households from municipal solid waste incinerators	-		-	Dietary intake was identified as the predominant exposure pathway, accounting for more than 90% of total exposure. Among dietary sources, chicken was the major contributor, representing over 75% of dietary exposure, followed by eggs and rice.
				Food	Homegrown rice, egg, and chicken samples from 20 exposed households	-		Mean concentrations of ΣDL-PCBs, expressed as TEQs, were 1.08 pg TEQ/g fat in upwind chicken samples and 1.09 pg TEQ/g fat in downwind chicken samples.	
				Soil	From around 20 exposed households	-		-	
Esen F et al. (47)	June 2019 to August 2019	Bursa (Türkiye)	38 PCB congeners	Dust	Collected from living room and bedroom floor surfaces in 20 exposed households.	-		-	-
		Air		Sampling sites were distributed as follows: one in the industrial zone (B1), one in the agricultural zone (B2), and two in semi-urban areas (B3–B4).	12	Adults and children	Ranged from 1163.93 to 1737.45 pg/m ³		
		Soil			24		Ranged from 3.94 to 15.21 ng/g dw		
		Air		Sampling sites Y1–Y3 in Yurimaguas were classified as semi-urban areas.	12		Ranged from 367.32 to 687.89 pg/m ³		
Soil		18	Ranged from 4.79 to 10.51 ng/g dw						
Adesina OA (48)		Nigeria	15 PCB DL- and NDL congeners	Air	Ambient air around a municipal solid waste (MSW) open burning site	-	Adults and children in the university community and the rural community around the university	Ranging from 3.12 to 5.04 ng/ m ³	-
				Soil	At six different locations at the MSW dumpsite			Ranging from 23.72 ng/g to 28.66 ng/g	
Saktrakulkla P et al. (15)	2018-2019	North America (East Chicago, Indiana, Columbus Junction, Iowa)	205 PCB congeners	Food	26 food items (and 134 food items from DHQ II)	-	Mothers and children	Ranging from 1.2 to 120 µg/year	Dietary exposure is comparable to inhalation exposures, although diet remains a significant route of PCB exposure.
				Air	-	-		Ranging from 0.2 to 160 µg/year	

Table 1. Continued.

Reference	Year	Place of Sampling	Kind of measured PCBs	Source of exposure	Type of sample	Sample size	Exposed community	Concentration (measurement unit)	The largest contribution of exposure for ΣPCBs
Ampleman MD et al. (41)	-	North America	40 PCB congeners	Food	Market basket of North America and NHANES survey food ingestion rates	-	Adolescent children and their mothers	Average Σ ₄₀ PCB dietary exposure: 82.8 (µg/yr)	Dietary
			201 PCB congeners	Air	Indoor and outdoor PCB air concentration	293		Σ ₂₀₁ PCB inhalation exposure: 2.43–12 (µg/yr)	
	2006 to 2011		Total 6 NDL-PCB	Food	Food samples collected within the framework of the second French Total Diet Study (EAT 2).	212		Σ ₆ NDL-PCB Dietary exposure: 2.71E – 03 (µg/kg/d)	
Enault J et al. (18)		France	6 NDL-PCB (28, 52, 101, 138, 153, 180)	Drinking water	Collected during routine monitoring and quality control of water produced and distributed by Lyonnaise des Eaux.	~1860	French adult population	Σ ₆ NDL-PCB Drinking water exposure: 4.57E – 04 (µg/kg/d)	Dietary
					Wheat	28		Σ ₃₃ PCB: 0.15–2.22 ng/g dw (Estimated daily intake: 1044 pg/kg/d)	
					Rice	28		Σ ₃₃ PCB: 0.05–9.21 ng/g dw (Estimated daily intake: 2825 pg/kg/d)	
Mahmood A et al. (46)	Jan 2013 to June 2013	Pakistan	33 PCB congeners (DL and NDL)	Air	Outdoor air at sampling sites	6		Σ ₃₃ PCB: 41–299 pg/m ³	
				Soil	Surface soil samples	28		Σ ₃₃ PCB: 0.70–30.5 ng/g dw	
	1992 to 1996			Food	Market basket samples collected in six Canadian cities were classified into three food groups: meat & eggs, dairy products, and fish.	-		-	
Mato Y et al. (42)		United States	18 PCB congeners				Adult living in the Midwestern United States		Dietary
	2006 to 2007			Air	Outdoor air at the sampling sites and indoor air were considered; however, no indoor PCB measurements were available for Chicago.	184		-	
	1998 to 2002			Food	Various kinds of foodstuff	54 data points in 1998–2001; 36 data points in 2002			
				Air		1028 sites in 2001; 989 sites in 2002:			
Norström K et al. (17)		Japan	PCDDs, PCDFs, and dioxin-like PCBs (dioxins)*	Soil		3735 sites in 2001; 3300 sites in 2002:		Average human uptake of dioxin: 1.68 pg-TEQ/kg-bw/day (in 2001) and 1.52 pg-TEQ/kg-bw/day (in 2002)	Diet accounted for more than 90% of the total intake.
	2001 to 2002			Purified and raw water from water purification plants		46 data points for purified water and 34 data points for raw water in 2001			
Duarte-Davidson R & Jones KC (45)	1986 to 1992	UK	24 PCB congeners	Food	Domestic food consumption data from ~ 7000 households in Britain		UK population	The average ΣPCB intake: 0.53 µg/person/day	Dietary intake accounted for 97% of the total PCB exposure.
				Water					
				Air					

* The sum of the concentrations of three types of dioxins has been used for total estimates

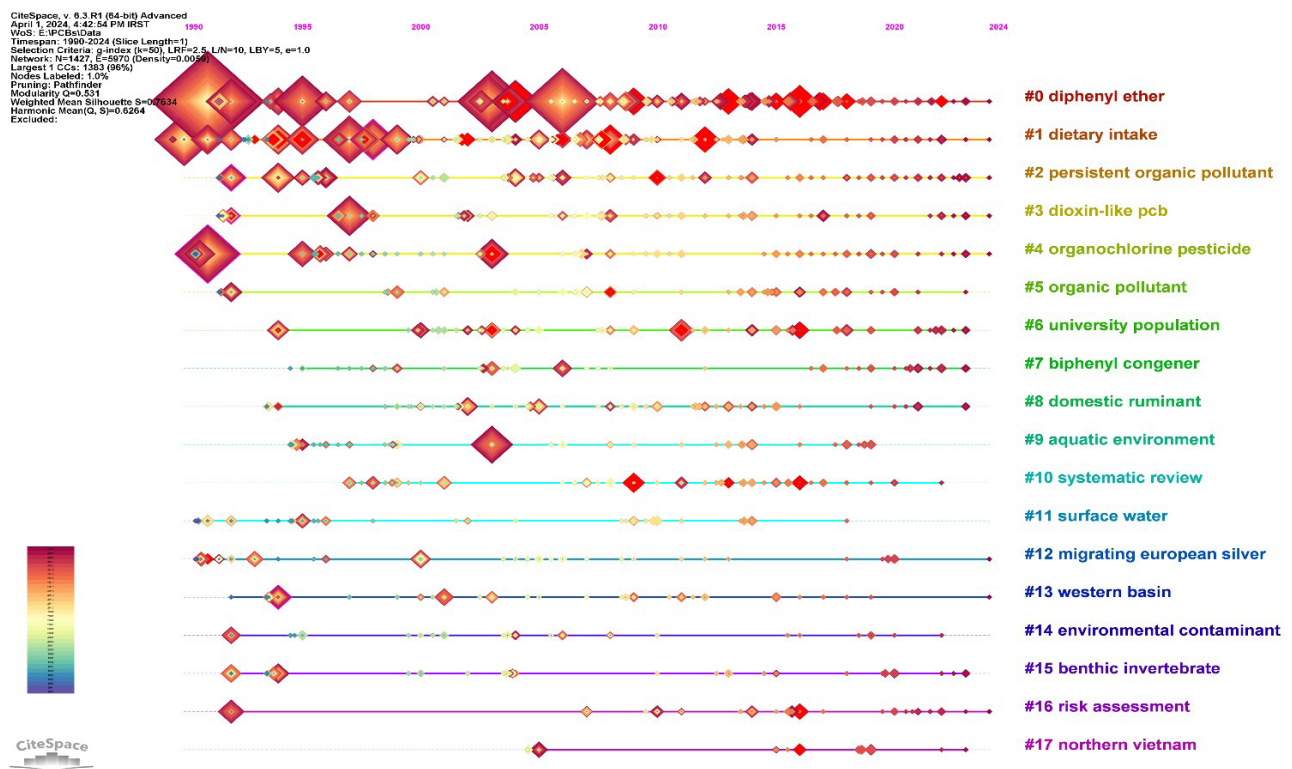


Figure 2. The main and active clusters of the study

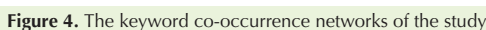
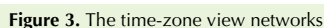
from 1990 to 2024. In the early years, research primarily focused on environmental occurrence, bioaccumulation, tissue distribution, polychlorinated biphenyls, toxicity, exposure, and the food web. Between the early 2000s and approximately 2012, research expanded toward environmental contamination, sediment pollution, persistent organic pollutants, brominated flame retardants, ecological risk, and contamination assessment. More recent studies (2013–2024) have increasingly emphasized human health-related topics, including endocrine disruption, health risks, organochlorine pesticides, particle size distribution, road dust, and street dust, indicating a shift from environmental monitoring to human exposure assessment and risk evaluation. Overall, the time-zone analysis demonstrates a clear evolution from studies describing environmental contamination to more integrated investigations addressing human health implications and exposure pathways. Figure 4 shows the keyword co-occurrence networks, where each term's size is proportional to its frequency. Polychlorinated biphenyls, brominated diphenyl ethers, persistent organic pollutants, polycyclic aromatic hydrocarbons, and exposure to PCBs were the dominant keywords indicating the principal research themes in the retrieved literature.

Discussion

This systematic review summarized evidence from eleven studies investigating PCB exposure pathways and their relative concentrations across diverse environmental settings. Overall, the available evidence remains geographically uneven, with most studies conducted in North America and East Asia, and comparatively limited data from large parts of Africa, South America, the

Middle East, and parts of Asia. This imbalance highlights a critical gap in the global characterization of PCB exposure pathways despite the absence of geographical restrictions in the present review. Studies reported substantial variability in PCB concentration profiles and congener composition across regions, reflecting differences in geographic location, historical usage patterns, banning timelines, environmental persistence, and bioaccumulation processes (35,49,50). Congener-specific physicochemical properties, environmental transformation processes such as degradation and photolysis, and co-exposure with other contaminants further influence these variations (35,49,51).

In this review, the number of assessed congeners ranged from 6 to 205. Importantly, differences in congener selection are a major source of methodological heterogeneity, potentially affecting both exposure assessment and the interpretation of health risks (5,35,51). Advances in analytical techniques have enabled broader congener detection; however, inclusion of dioxin-like congeners adds complexity to exposure and risk characterization because of their distinct toxicological mechanisms compared with other PCB classes (35,51). Although international monitoring frameworks recommend a limited set of indicator congeners (PCB 28, 52, 101, 138, 153, 180, and 118) for routine assessment (52) and some studies suggest that the sum of congeners 138, 153, and 180 may serve as a surrogate indicator of total body PCB burden due to their high environmental abundance (51), the findings of this review indicate substantial variability in congener selection across studies. Previous research has demonstrated that congener coverage varies widely depending on study objectives and matrices, from targeted subsets to full congener profiling, including assessments



Consistent with the present study and previous literature (10,56), dietary intake was the dominant exposure route in the general population, particularly through consumption of animal-derived foods such as fish, eggs, meat, and dairy products (11,13,15,57). While inhalation and dermal exposure are more relevant in occupational settings, their contribution in non-occupational populations remains less well characterized (58,59). Other pathways, including drinking water and dermal contact (with contaminated water or soil), appear to contribute minimally under typical

Another important gap identified is the limited integration of health risk assessment into exposure studies, with only four studies incorporating it (43,46–48). Researchers applied different methodological frameworks, including TEQ (toxic equivalency)-based and total PCB approaches, reflecting the complexity of PCB toxicity assessment (49,51,58). Because dioxin-like and non-dioxin-like congeners have distinct toxicological mechanisms, the choice of assessment method can substantially influence risk estimates (49,51). While TEQ approaches are widely used, they may not fully capture risks from more abundant non-dioxin-like congeners in environmental mixtures (49,51,58). This limitation is particularly relevant considering that real-world exposures involve complex mixtures rather than individual congeners (58). Collectively, these findings suggest that PCB risk assessment needs greater methodological harmonization,

particularly for studies evaluating multi-pathway exposure scenarios.

Visualization analyses indicated that dietary intake, persistent organic pollutants, and PCB risk assessment have been the dominant research themes, with increasing attention to risk assessment and dioxin-like PCB toxicity in recent years. However, researchers have paid comparatively little attention to integrated assessment of multiple exposure pathways, despite its importance for realistic risk characterization. Consistent with these trends, several studies included in this systematic review conducted health risk assessments for at least one PCB exposure source (43,46–48). Reported health risks varied across populations and exposure scenarios, with elevated non-carcinogenic risks observed in highly exposed groups (43), while carcinogenic risks were generally below acceptable thresholds (43,47), except in heavily contaminated regions (48). These findings suggest that chronic PCB exposure continues to pose a potential public health concern, particularly in vulnerable populations and individuals residing in highly contaminated environments.

However, several limitations warrant consideration. The included studies were geographically limited, reducing global representativeness, and substantial methodological heterogeneity (including variations in study period, type and number of congener selection, analytical methods, and reporting concentration units) complicated direct comparisons and meta-analysis. Nevertheless, consistent evidence has identified dietary intake as the predominant route of PCB exposure in the general population, primarily through animal-derived foods. Thus, despite limited quantitative comparability, the overall direction of findings remains consistent. Given that PCBs are classified as “probably carcinogenic to humans,” further research across diverse populations and regions is warranted. Finally, PCB exposure should be interpreted within the broader context of multi-pollutant environments, as individuals are simultaneously exposed to mixtures of persistent organic pollutants, heavy metals, pesticides, and other chemicals. These co-exposures may interact through additive or synergistic mechanisms, influencing both exposure dynamics and health outcomes. Therefore, future epidemiological and exposure assessment studies should adopt multi-pollutant approaches to better characterize combined environmental exposures and their potential health implications in human populations (65,66).

Conclusion

In summary, this systematic review synthesized current evidence on PCB exposure pathways and their relative contributions to human exposure and health risks. The evidence base remains limited and geographically concentrated, with most studies conducted in the United States and China, and congener selection varies widely (6–205 congeners). Overall, dietary intake—particularly from animal-derived foods—was identified as the predominant exposure pathway. Notably, only one study comprehensively assessed all major exposure routes, and

few studies incorporated health risk assessment, although such approaches have gained increasing attention over the past decade.

Future epidemiological research should prioritize large-scale, standardized international designs to better quantify the contribution of PCB exposure pathways and associated health risks across age groups. Methodological harmonization, including consistent PCB congener selection, standardized exposure assessment methods, and uniform reporting units across environmental and biological matrices, is essential to improving comparability. In addition, adopting multi-pathway and longitudinal approaches, expanding research in underrepresented regions, and integrating comprehensive risk assessment frameworks would strengthen the evidence base. A better understanding of PCB exposure sources and population-level risks can help policymakers develop more effective environmental regulations, monitoring systems, and preventive strategies.

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Competing Interests

The authors declare no competing interests.

Data Availability Statement

All the data analyzed during this study are included in this article.

Ethical Approval

Not applicable.

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Supplementary Files

Supplementary File contains Table S1-S2

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