Nevondo *et al. J Environ Expo Assess* 2022;1:10
DOI: 10.20517/jeea.2022.02

Journal of Environmental Exposure Assessment

Review

Open Access

A review on levels of polychlorinated naphthalenes in matrices with emphasis on knowledge and research gaps priorities in Africa

Vhodaho Nevondo, Okechukwu Jonathan Okonkwo

Department of Environmental, Water and Earth Sciences, Faculty of Science, Tshwane University of Technology, Pretoria Central 0001, South Africa.

Correspondence to: Prof. Okechukwu Jonathan Okonkwo, Department of Environmental, Water and Earth Sciences, Faculty of Science, Tshwane University of Technology, 175 Nelson Mandela Drive, Pretoria Central 0001, South Africa. E-mail: OkonkwoOJ@tut.ac.za; Prof. Vhodaho Nevondo, Department of Environmental, Water and Earth Sciences, Faculty of Science, Tshwane University of Technology, 175 Nelson Mandela Drive, Pretoria Central 0001, South Africa. E-mail: vhodahonevondo@gmail.com

How to cite this article: Nevondo V, Okonkwo OJ. A review on levels of polychlorinated naphthalenes in matrices with emphasis on knowledge and research gaps priorities in Africa. *J Environ Expo Assess* 2022;1:10. https://dx.doi.org/10.20517/jeea.2022.02

Received: 18 Jan 2022 **First Decision:** 9 Feb 2022 **Revised:** 18 Mar 2022 **Accepted:** 29 Mar 2022 **Published:** 15 Apr 2022

Academic Editor: Stuart Harrad **Copy Editor:** Jia-Xin Zhang **Production Editor:** Jia-Xin Zhang

Abstract

Polychlorinated naphthalenes (PCNs) were listed as Persistent organic pollutants in the Stockholm Convention, in May 2015, because of their adverse health and environmental effects. PCNs production began in the early 1900s when they were used extensively in several consumer goods as fire retardants. However, because of their health and environmental implications, the production and use of PCNs chemicals were voluntarily banned in many countries in the 1970s and 1980s. However, PCNs are still detected in different environmental samples including air, water, sediments, soil, indoor dust, biota, consumer products, human diet, blood and serum today, as a result of their historical use and unintentional production. Thus, PCNs can be released into the environment throughout their life cycle. It becomes, therefore, crucial to monitor them in different environmental compartments. To date, about 163 reports on PCNs levels in several matrices have been published in different parts of the world. It was reported that toxic PCNs such as chloronaphthalenes 66, 67 and 73 are prevalent in most samples; thus, there is a need to continuously monitor these congeners in our environment. However, there are sparse studies related to PCNs levels, not only in consumer products, leachates and sediment samples from landfill sites in Africa but also in other matrices, leaving a huge research gap that must be prioritized. To date, only about 3 studies on PCNs have been published in Africa, bearing in mind that there is no documented evidence of any known production of PCNs

© The Author(s) 2022. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, sharing, adaptation, distribution and reproduction in any medium or format, for any purpose, even commercially, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

in the continent. Thus, a wide research gap in PCNs studies still exists in Africa. There is an urgent need, therefore, to conduct studies and establish robust PCNs inventories in Africa. The present review examines the existing knowledge on PCNs levels and trends in Africa, and identifies research gaps that ought to be addressed so that the scale of PCNs distribution in the global environment can be known.

Keywords: Persistent organic pollutants (POPs), polychlorinated naphthalenes (PCNs), concentrations, congeners, matrices, Africa

INTRODUCTION

Polychlorinated naphthalenes (PCNs), commonly known as chloronaphthalenes, are among the chlorinated polycyclic aromatic hydrocarbons comprising 75 congeners, with two-ringed aromatic compounds containing 1 to 8 chlorine atoms per naphthalene molecule as shown in Table 1[1-3]. PCNs, are lipophilic and semi-volatile, and are synthesized by reacting molten naphthalenes and chlorine gas at a temperature that is slightly above the melting point of the desired product in the presence of iron (III) or antimony(v) chloride catalysts[4]. This reaction gives rise to complex liquids and waxes of naphthalenes with high melting points[5]. The synthesis of PCNs was authorized in 1909, and their applications grew during World War I[4]. According to Falandysz *et al.*[6] PCNs were produced under different trade names such as Halowax, Nibren wax, Perna wax and Basileum, and Seekay waxes, Clonacire, Cerifal materials, and N-oil and N-wax. Furthermore, PCNs were the second largest high volume halogenated organic chemicals after hexachlorobenzene[7]. About 150,000-400,000 metric tons of different technical PCN-mixtures were produced from large-scale producers in countries including Germany, the USA, France, Italy, Japan, Poland and the United Kingdom[8,9]. However, because of their health and environmental implications, the production and use of PCNs chemicals were voluntarily banned in many countries in the 1970s and 1980s[10]. Despite the banning, PCNs are still detected in different matrices hitherto. In Africa, no production of PCNs has been reported yet. However, Babayemi *et al.*[11] pointed out that large volumes of PVC and other polymers with additives that may contain chlorinated paraffins (CPs) have been imported in large quantities by some African countries, which can also be considered a potential source of PCNs.

Given their physicochemical properties such as good thermic balance, water resistance, mucus repellent, insulating properties, flame-retardance and inertness, PCNs were earlier applied in large quantities as flame-retardants in various consumer products[3,12]. Thus, many products may contain 5%-30% by weight of PCNs[3]. Most of PCNs were widely used as technical mixtures in cable insulation, plasticizers, paints, textile and paper industries, wood preservation, engine oil additives, electroplating masking compounds, dye carriers, and capacitors[6]. PCNs can be discharged into the environment throughout their life cycle during the manufacture, use and disposal of PCN-containing consumer products, coking plants, metallurgical plants and waste incinerators[13,14]. Other sources of PCNs discharge in the environment include historical usage of technical PCB formulations, which exist in small quantities of up to 1%[9,15,16]. The burning of fuels such as biomass and forest fires, metal smelting and sintering, and the formation of PCNs during cooking process are also among other sources[3,17].

Because of their toxic health effects on both humans and animals, PCNs were included as Persistent organic pollutants (POPs) in the Stockholm Convention Annexes A and C in May 2015[9]. Moreover, PCNs were added to the protocol on POPs under the Convention on Long-Range Transboundary Air Pollution in December 2009[18]. The major pathway of human intake of PCNs is via dietary intakes such as eggs, milk, and fish, which is accounted for about 90% of their daily individual intake[19], although other routes such as inhalation and dermal contact are also possible[3,17]. The toxic effects of PCNs in both animals and humans include mortality, embryotoxicity, hepatotoxicity, immunotoxicity and induction of dermal lesions,

Table 1. PCNs homologues

Congener group	Acronym	Molecular formula	No. of individual congeners
Monochloronaphthalenes	MonoCN	$C_{10}H_7Cl$	2
Dichloronaphthalenes	DiCN	$C_{10}H_6Cl_2$	10
Trichloronaphthalenes	TriCN	$C_{10}H_5Cl_3$	14
Tetrachloronaphthalenes	TetraCN	$C_{10}H_4Cl_4$	22
Pentachloronaphthalenes	PentaCN	$C_{10}H_3Cl_5$	14
Hexachloronaphthalenes	HexaCN	$C_{10}H_2Cl_6$	10
Heptachloronaphthalenes	HeptaCN	$C_{10}HCl_7$	2
Octachloronaphthalenes	OctaCN	$C_{10}Cl_8$	1

Adapted from data compiled by Agunbiade *et al.*[3]. PCNs: Polychlorinated naphthalenes.

teratogenicity and carcinogenicity[3,20,21]. Consequently, studies have reported PCNs levels in human adipose tissue, liver, breast milk and blood serum[22-24]. In Canada, a screening exercise reported PCNs levels with 2-8 chlorine atoms were released into the environment at levels that may have immediate or long-term harmful effects on the environment. Therefore, PCNs met the criteria outlined in the persistence and bioaccumulation regulation under the Canadian Environmental Protection Act 1999[25]. It is, however, noteworthy to consider that currently, there are no PCNs regulations in the continent of Africa.

Hitherto, efforts have been made to characterize POPs chemicals, including CPs, in several matrices such as atmosphere, river, sediments, soil, indoor dust, biota, consumer products, human diet, blood and serum in Africa[26-41]. However, in the African continent, studies on PCNs in environmental matrices are yet to be investigated, hence the limited available information[3,10,42,43]. Furthermore, according to Hogarh *et al.*[10], PCNs are one of the least researched halogenated organic pollutants in Africa. Electronic gadgets and industrial wastes that may contain PCNs are exported from developed countries to developing countries, and this can serve as a source of transferring the PCNs pollution burden from industrialized nations to developing ones[44]. Additionally, most developing countries lack safety measures and regulations for the exposed population[44]. Currently, few studies have reported the PCNs levels in consumer products, leachate and sediment samples from landfill sites. The present review, therefore, examines the existing knowledge on PCNs levels and trends in the continent of Africa, and identifies knowledge gaps that should be addressed so that the scale of PCNs distribution in the global environment can be known.

PRODUCTION, USES AND RELEASES OF PCNS

Production

Historically, the synthesis of PCNs was authorized in 1909, and their applications grew during World War I[4]. However, the production of PCNs declined after World War II when polychlorinated biphenyl (PCBs) were introduced, yet, they remained high volume chemicals until the 1970s[9,45]. PCNs were synthesized by reacting molten naphthalenes with chlorine gas at a temperature that is slightly above the melting point of the desired product in the presence of iron (III) or antimony (v) chloride catalysts[3-5]. The crude product was further treated with sodium carbonate (Na_2CO_3) or sodium hydroxide (NaOH) to give a final product of complex mixtures of naphthalenes that range from liquids to waxes with high melting points[3,5,46]. PCNs can also be produced via chlor-alkali and metal productions[47]. According to Falandysz *et al.*[6], PCNs were produced under different trade names such as Nibren wax (Germany), Seekay waxes (UK), Clonacire (France) and Halowax (USA). Other trade names include Perna wax, Basileum and N-oil [Table 2][9].

Table 2. Trade names, composition and manufacturers of technical PCN mixtures*

Trade name		Composition	Manufacturer
Halowax	1031	mono-diCN (22-70% Cl)	Koppers Co Pittsburg, PA, USA
	1000	mono-diCN (26% Cl)	
	1001	di-penta (50% Cl)	
	1099	di-pentaCN (52% Cl)	
	1013	tri-pentaCN (56% Cl)	
	1014	tetra-hexaCN (62% Cl)	
	1051	hepta-octaCN (70% Cl)	
Basileum	SP-70	mono-diCN (80% Cl)	Desowag Bayer, Germany
Nibren wax	D88	(50% Cl)	Bayer Leverkusen Germany.
	D116 N	(50% Cl, estimated from melting point)	
	D130	(60% Cl, estimated from melting point)	
Seekay wax	R68	(46.5% Cl)	ICI Runcorn, UK
	R93	(50% Cl)	
	R123	(56.6% Cl)	
	R700	(43% Cl)	
	RC93	(50% Cl)	
	RC123	(56.5% Cl)	
Clonacire wax	95	(50% Cl)	Prodelec, Paris, France
	115		
	130		

Adapted from UNEP Draft guidance documents for inventories of PCNs[9];*Mono-CNs are not listed as POPs in the Stockholm Convention. Mono-CN products might, however, contain higher chlorinated PCNs listed in the Convention. UNEP: United Nations Environmental Programme; PCNs: polychlorinated naphthalenes; POPs: persistent organic pollutants.

Because of the health and environmental issues associated with PCNs, the majority of countries in North America and Europe prohibited the manufacture and application of PCNs in the 1980s[48,49]. According to Hayward, between 50,000 and 150,000 tons were produced in the USA from 1910 to 1960[50]. In Japan, the total production volume of PCNs w about 5,000 tons between 1940 and 1976[51]. Although the production of PCNs was ceased in the mid-1960s in the UK, small quantities of PCNs were still manufactured in the 1970s[52]. PCNs were manufactured as additives in products until the early 2000s, where PCN-containing consumer products were still found in the Japanese market[9]. Except for some small-scale production of octachloronaphthalenes, China is reported to have never produced technical PCN formulations[10]. There are no documented records of any PCNs production in Africa. However, a publication in 2015 showed that about 10,000 tons of CPs were produced per year in South Africa, indicating the existence of production of PCNs in the continent[53].

Industrial uses

Because of their physicochemical properties, such as stability, flame retardation, electrical insulating, fungicidal and insecticidal properties, PCNs were used as additives in different consumer products [Table 3][9,14]. PCNs were predominantly used in cable insulation, fluids and impregnate in capacitors or condensers, wood treatment, additive in paints and dye carriers, dye feedstock, production of engine oils and transformer fluids[9]. Tri- to octa-CNs were mainly used in different mixtures, as shown in Table 3. PCNs mixtures consisting of mono- and di-CNs were used in gauges and instrument seals, fluids in heat exchangers, solvents for colour dispersion, vehicle crankcase additives, fluids in motor tune-up and dyes. Moreover, Helm *et al.*[54] also pointed out that the use of PCNs in fire retardation and as dielectric fluids in capacitors was authorized in the 1900s. Other uses include wood, textile and paper treatment for fungal protection, plasticizers, additives in oil, casting materials for alloys and lubricants for graphite electrodes;

Table 3. Former PCNs uses in consumer products

Sector	Application
Transformers and Capacitors	Capacitor impregnates Transformer and capacitor fluids
Batteries	Separator in storage batteries
Plastics and cables	Cable covering compositions Additive in plastic Intermediate for polymers and fire-retardants in plastics
Rubber	Additive in Neoprene
Sealants	Water proofing
Paints, lacquers, dyes/dye carrying agents	Anti-corrosion/underwater paints and lacquers Raw material/feedstock dye carriers
Wood preservative / fungicide	Impregnation of wood
Textile and paper industry	Water proofing of paper and textiles Binders in paper coating and impregnation
Oil additives and lubricants	Oil additives for gear and machinery lubrication Oils in the mining sector Vehicle oil additive Oils for refracting index testing
Military use	Fogg ammunition; smoke grenades Inert artillery and mortar projectiles Paper filter for gas masks in WW1 Paints for ships and metals Military vehicles and equipment

Adapted from UNEP Draft guidance document for inventories of PCNs[9].UNEP: United Nations Environmental Programme; PCNs: polychlorinated naphthalenes.

electronic and automotive applications, paper binding, coating and impregnation; ceramic binding, lubricants for grinding and cutting, moisture proofing and sealant[45].

In Europe, PCNs were used in paints until the 1980s, but their use declined considerably after the 1980s[55]. The most recent available information on PCNs application in casting material was reported in Germany and the former Yugoslav Republic of Macedonia until 1989[56]. It was further reported that PCNs were used as additives in chloroprene rubber until early 2000. About 12.6 tons of PCNs were used to produce 259 tons of synthetic chloroprene rubber (Neoprene FB), of which 207 tons were for export and the remainder used in Neoprene FB rubber belts and sealants production[9]. Sumitomo 3M Co. Ltd in 2002, imported 54 tons of Neoprene FB rubber compounds from Canada, which was used in manufacturing more than 210,000 cans of aerosol adhesives[57]. Manufacturers in Japan were directed to stop exporting and recall all PCNs-containing products[57]. Some uses of PCNs include fog ammunition and inert artillery and mortar projectiles for military operations[9]. In 1981, about 15 tons/year were used as capacitors dielectrics and refractive index tests in the USA[9]. In consideration of the aforementioned manufacture of CPs and the importation of polymers into Africa, the presence of PCNs in different applications becomes quite clear. These prompt the need to develop robust PCNs inventories and regulations in Africa.

Environmental releases

PCNs are ubiquitous in the environment. Studies have shown that PCNs are conveyed from their production sites to far distances globally either by wind, water or living organisms resulting in their bioaccumulation over a long period in the environment[9]. Of all the sources via which PCNs are released into the environment, combustion has been identified as the major source. Above 80% of PCNs is estimated to have been emitted into the European atmosphere from this source[12]. According to Helm and Bidleman, the present PCNs concentrations in the environment are attributed to sources from past uses of technical

mixtures and combustion from WEEE, waste incinerators, metal refining and steel production[58]. The following PCNs congeners PCN-20, -17/25, -26, -13, -18, -44, -36/45, -29, -27/30, -39, -35, -52/60, -50, -51, -54, -66/67, and -73 are related to combustion[54]. In the UK, elevated concentrations of polychlorinated naphthalene congeners-24 and -50 in the atmosphere have been attributed to coal and wood combustion[59]. Research reports have shown that the part played by combustion sources in the PCN burden on the environment has been increasing[60]. For example, Pan *et al.*[61] conducted a study on PCNs in dated sediment cores from Jiaozhou Bay in the Yellow Sea region (East of China). The results showed that PCN flux maxima occurred in the mid-1970s and late-1990s outside and inside the bay, respectively. This observation was attributed to the influence of different sources of PCN pollution in the Yellow Sea region. The chronology of PCN pollution elucidated from characteristic congener patterns from thermal sources indicated that PCN sources in the 1950s arose mainly from wood and coal burning, followed by a suggested input of technical PCN pollution from the 1970s to 1990s. The congener patterns in the uppermost layers of the cores suggested that the contribution from municipal solid waste combustions may have become more significant in recent years[61].

Industrial processes and inadvertent production of PCNs

Moreover, Liu *et al.*[14] and Bidleman *et al.*[12] reported that PCNs are still released into the environment through different industrial and other thermal processes such as refuse burning, manufacturing of iron and steel, nonferrous melting procedures, cooking processes and manufacturing of cement despite the prohibition of their production in most countries since the 20th century[62-66]. Secondary copper smelting processes from a Chinese factory were recently reported to emit about 65%, 27% and 8% of PCNs into the environment during the three different stages of production, respectively- feeding fusion, oxidation and de-oxidation[3,64]. PCNs concentrations in the stack gas samples for the three stages ranged from 477.0-762.5 ng/m^3. Polychlorinated naphthalenes can also be released into the environment from sites of production [Table 4][9]. High releases and contamination at former PCN-production sites to air (25-2900 ng/m^3), water (up to 5500 ng/L) and soil (up to 1300 mg/kg) have been reported, which indicates past pollution and possible current contamination at and around PCN-production sites[9].

Another important source of PCNs in the environment is their inadvertent occurrence as contaminants in other similar industrial chemicals such as commercial PCB mixtures, Aroclors, Kanechlors, Phenoclors and Sovol[17]. Profiles of PCN congeners (tri- to octa) in 18 different commercial PCB mixtures have been presented, and an estimation of global inadvertent by-production of approximately 169 tonnes was reported[15]. PCNs concentrations ranged from 5.2-67 μg/g in Aroclors and 731 μg/g in Sovol. PCN congener profiles in PCB mixtures varied depending on the type of mixture and the chlorine content, but also on other conditions such as selective volatilisation of the lower chlorinated congeners (mono-, di- and tri-CNs)[15]. PCNs are also released into the environment during the cooking process[3,17]. In a study on potential dietary sources, Dong *et al.*[67] reported on the potential for direct formation of PCNs in food during the cooking process. The study involved heating commonly used cooking oils (peanut and olive) known to be free of PCNs in the presence of sucralose (a synthetic sweetener) at elevated temperatures. Sucralose thermally decomposed at high temperatures and acted as a chlorine source during the formation of a range of PCN congeners, which were detected in the fumes emitted during the experimental process. The total concentrations of PCNs found in the peanut and olive oil fumes were 490 pg/g and 240 pg/g, respectively[67]. Moreover, according to Ren *et al.*[68] municipal solid waste (MSW) incineration is a widely adopted technology for treating waste. During incineration, PCDD/Fs, PCBs and PCNs, can be formed and released into the ambient environment unintentionally. The emission of these chemicals is of public concern because of their toxic health effects.

Table 4. PCNs concentrations in matrices impacted by industrial sources

Sample matrix	Levels of PCNs
Soil at former PCN production site	1300,000 µg/kg
Soil at chloralkali plant	7400-18,000 µg/kg
Soil at electric arc furnace	10 µg/kg
Soil background	0.003 µg/kg
Sediment at hot spot	100,000 µg/kg
Sediment at chloralkali plant	260-23,000 µg/kg
Sediment background	0.2 µg/kg
Sewage sludge China	1-11 µg/kg
Surface water production site	up to 5500 ng/l
Air at workplace PCN production	14,500,000 ng/m^3
Ambient air at PCN production site	25-2900 ng/m^3
Ambient air at electric arc furnace	1.6 ng/m^3
Ambient air across Ghana	0.027-0.095 ng/m^3
Air at e-waste recycling,Ghana	0.38 ng/m^3
Air background	0.001-0.040 ng/m^3

Adapted from UNEP draft guidance document for inventories of PCNs[9]. UNEP: United Nations Environmental Programme; PCNs: polychlorinated naphthalenes.

Landfills and open dumping

Landfills with wastes containing PCNs can be considered contaminated sites with the potential to release PCNs into the environment through landfill leachates and gas[69]. In Spain, Martí and Ventura analysed groundwater samples from four boreholes in the Llobregat aquifer, a study area that previously served as a dumping site[70]. The levels PCNs ranged from 0.0005-79.1 µg/L, while tetra-CNs were the dominant congeners. The Basel Convention, Annex VIII, has classified waste containing PCNs as hazardous and low POP content threshold for PCNs was set at 10 mg/kg or 50 mg/kg[9]. It was further stated that wastes containing PCNs above this concentration should be handled in a sound environmental manner to destroy the POP content or irreversibly transformed according to the methods described in the Basel Convention technical guidelines[9]. Nonetheless, in Africa, most polymeric wastes are disposed of with MSW with minimal formal recycling of approximately 10% either by landfilling or open dumping[29,53]. There is hardly any thermal or energy recovery from waste (incinerators or cement kilns) in Africa. Thus, by far, the largest share of polymeric waste ends up in dumpsites or landfills, which may serve as a source of PCNs emissions into the environment[11,53]. Moreover, the open burning of solid waste, inclusive of polymeric products, is prevalent in most African countries[68]. As a result of the lack of effective solid waste management, mixed wastes, including polymers, end up in dumpsites where they are burnt, resulting in the release of POPs into the environment[53]. Polymeric products normally contain a wide range of additives such as plasticizers, flame-retardants, antioxidants, acid scavengers, light and heat stabilizers, lubricants, pigments, antistatic agents, slip compounds, and thermal stabilizers, which are used for various purposes[71-74]. Many of these additives are classified as endocrine disrupting chemicals. Several other chemicals listed as endocrine-disrupting POPs include PBDEs, HBB, HBCD, SCCPs, and PFOA[11]. These releases of POPs from afore-mentioned products can, therefore, be regarded as sources of PCNs to air, soils, biota industrial areas and in-house dust, resulting in human exposure.

ROUTES OF EXPOSURE AND TOXICITY

The principal route via which humans are exposed to PCNs is through dietary intake[13,17]. According to Martí-Cid *et al.*[75] and Llobet *et al.*[76], dairy products are the major sources of given population exposure, amounting to about 90% of ingestion of PCNs/day/person. The presence of PCNs in sea and fish has been

reported globally[77-80]. In addition, PCN congeners with high masses have also been detected in drinking water[79,81]. During the 1930s and 1940s, a study by Hayward reported occupational health hazards associated with PCNs exposure, and these included chloracne as a result of severe skin rashes and liver disease that may have resulted in the deaths of some workers[50]. The toxic effects of PCNs in both animals and humans include mortality, embryotoxicity, hepatotoxicity, immunotoxicity and induction of dermal lesions, teratogenicity and carcinogenicity[3,20,21]. A set of thermodynamic data obtained by Falandysz *et al.*[82] indicated that continuous deleterious effects of 75 PCN congeners on living organisms steadily increase from mono-CN to octa-CNs. All PCN congeners are planar compounds, which dissolve easily in lipids (lipophilic), and they structurally resemble the highly poisonous 2,3,7,8 -tetrachlorodibenzo-*p*-dioxin (TCDD)[3]. The brominated or chlorinated counterparts are expected to show similar properties, although structural distortion due to the higher mass and size of bromine may influence the degree of planarity. The structural similarity of these molecules to the highly toxic TCDD molecule suggests an aryl hydrocarbon (AhR)-mediated mechanism of toxicity, also commonly referred to as dioxin-like toxicity[8]. Thus, some PCNs are included in the toxicity equivalency factor concept. It uses the relative effect potency (REP) determined for individual PCDD, PCDF, and PCBs compounds for producing toxic or biological effects relative to a reference compound, usually 2,3,7,8-TCDD. The total toxic equivalent is operationally defined by the sum of the products of the concentration of each compound multiplied by its TEF value and is an estimate of the total 2,3,7,8-TCDD-like activity of the mixture[83]. Suzuki *et al.*[83] also explained that PCN congeners cause dioxin-like effects due to the interaction of planar molecules with AhR, resulting in toxicological effects comparable to those of PCDD/Fs. Furthermore, the dioxin-like toxicity of PCNs depends on the planar structure and substitution of chlorine at lateral (β) positions (2,3,6,7) of the naphthalene ring[6]. Based on this assertion, there are seven PCN congeners which have their lateral positions filled with chlorine; CNs- 48 (2,3,6,7-TetraCN), 54 (1,2,3,6,7-PentaCN), 66 (1,2,3,4,6,7-HexaCN), 67 (1,2,3,5,6,7-HexaCN), 70 (1,2,3,6,7,8-HexaCN), 73 (1,2,3,4,5,6,7-HeptaCN), 75 (1,2,3,4,5,6,7,8-OctaCN). Although CNs-68 (1,2,3,5,6,8-HexaCN) and -69 (1,2,3,5,7,8-HexaCN) showed reasonably high dioxin-like toxicity, they both have one carbon at the β-position which is not substituted with chlorine[3].

Additionally, of the PCN congeners, studies have revealed that hexachloronaphthalenes (hexa-CNs) are the most dangerous, particularly hexa-CNs 66, and 67[6]. Effects including oxidative stress, accumulation of fats in the liver (hepatic steatosis), blood disorders (hematological disturbances), liver damage (hepatotoxicity) and loss of appetite (anorectic effect) were observed in rats administered with hexa-CNs[84,85]. Chicken oedema (characterized by loss of feathers) and X-disease (bovine hyperkeratosis) in cattle's characterized by symptoms such as vitamin A deficiency, hypersalivation, skin thickening (Pachyderma), hair loss, and on rare occasions, may result in death, have all been linked to PCNs exposure in animals[3]. Additionally, other health effects of PCNs on humans include eye irritation, tiredness, headache, loss of appetite, constipation leading to severe abdominal discomfort[86].

PCNS STUDIES IN DIFFERENT MATRICES

Like many other persistent organohalogenated compounds, PCN congeners are lipophilic in nature and can be transferred from one matrice to another, leading to bioaccumulation via the food chain[84]. Globally, biotic and abiotic matrices are usually contaminated with relatively small amounts of PCNs[6,58,78,85-88]. While reports on PCNs are slowly emerging from different regions of the world, information on the studies conducted so far in different matrices is discussed below.

Atmosphere

One of the main sources of POPs in the human body is the inhalation of particles with a diameter of less than 2.5 μm[89,90]. About 90% of these particles can enter the alveoli, and this can lead to heart and lung

diseases and even death[90]. PCNs can be adsorbed strongly by particles with large specific surface areas[91-93]. Mao *et al.*[94] analysed atmospheric background levels of PCNs in East China. The $\sum_{39}$PCNs levels ranged from 5.9-143 pg m^{-3}, slightly lower than the concentrations obtained from studies conducted across China but higher than those obtained from Japan and Korea[95,96]. Tri-CNs were the most predominant congeners accounting for 65% ∑PCNs, while tetra-CNs and penta-CNs recorded 22% and 11% of ΣPCNs, respectively. However, hexa-CNs to octa-CNs exhibited 2% of ΣPCNs. Compared with other studies, the observed composition profile is in agreement with the observations in Ghana, India, Japan, Korea and Pakistan, where tri-CNs and tetra-CNs exhibited more than 80% of ΣPCNs[10,97]. In another study, PCNs levels were determined in atmospheric particulates from secondary copper smelters surroundings in China[98]. The observed PCNs levels ranged from 4.76-9.89 pg m^{-3}. In comparison with other studies, the PCNs concentrations differed significantly from the levels observed in industrial areas in Shanghai, Taiwan and Beijing[96-100]. Zhu *et al.*[101] reported atmospheric PCNs concentrations in gas and particle samples in Beijing, China, and ΣPCNs concentrations in gas and particle fractions in the urban environment ranged from 6.77-25.90 pg m^{-3} and 0.17-2.78 pg m^{-3}, respectively. Table 5 is a summary of atmospheric PCNs studies worldwide.

Aquatic environment

River

Mahmood *et al.*[102] determined PCNs concentrations in water samples from River Chenab tributaries in Pakistan. The observed PCNs concentrations ranged from 178-489 ng/L, with polychlorinated naphthelene-75 as the most prevalent congener among $\sum_{39}$PCNs. Furthermore, PCNs concentrations among congeners decreased in the following order: PCN-75 (37%) > PCN-32 (10%) > PCN-39 (8%) > PCN-51 (6%) > PCN-16 and -23 (5%). These results were lower than the levels noted by Espadaler *et al.*[103]. Ishaq *et al.*[104] reported mean PCNs concentrations that ranged from 14-410 ng/L in water samples from Grenlandsfjords in Norway[104].

Sediment

According to Cetin and Odabasi, PCNs are likely to be deposited in reservoirs and rivers sediments, where they are subjected to partitioning, decomposition and transportation according to their physical and chemical properties[105]. Previously, research studies have indicated that sediment is a major sink for POPs and PCNs show high accumulation potential in sediment and biota[106,107]. Dat *et al.*[108] analysed PCNs concentrations in three core sediment samples from Feitsui Reservoir and one surface sample from Laojie River in Northern Taiwan[108]. PCNs concentrations in sediment samples from Feitsui Reservoir and Laojie River ranged from 0.012-0.05 ng/g^{-1} and 0.408-1.47 ng/g, respectively. In comparison with other studies [Table 6], PCNs concentrations were relatively lower. In Canada, McGoldrick *et al.*[18]conducted a study on suspended sediment samples, which were collected at selected locations within the GreatLakes, their connecting channels, and the St. Lawrence River in 2012. Of the selected sampling locations, the highest PCN concentration of about 264,000 ng g^{-1} was detected in suspended sediment samples from the Detroit River, which was attributed to very high concentrations of PCNs at the monitoring stations in the Trenton Channel (DR1159 & DR1161). In addition, hexa-CNs were the most abundant PCN congeners present in suspended sediments from the Detroit River (32%) and surficial sediments in the western basin of Lake Erie (35%) and Niagara Bar in Lake Ontario (23%).

Fish

According to Cui *et al.*[109], the presence of PCNs in fish is an indication of contamination as well as the transfer of contaminants throughout the food chain[109]. Moreover, studies have indicated that although fish is an important source of protein for humans, however, the PCNs concentrations in fish appear to be significantly more than in other foods. Therefore, fish is an important contributor to PCNs intake by

Table 5. Concentrations of PCNs in the troposphere reported in different parts of the world

Country	Sampling year	Concentration pg m^{-3}	Dominant homologue	Ref.
Arctic and Scandinavia	1994	10-46		[84]
Northern Atlantic Ocean	1994	29-71		[84]
British Isles	1994	34-340		[84]
Europe	1994	22-170		[84]
Chicago, IL, USA	1994	24-180		[84]
British Isles	1998	22-160		[84]
British Isles	1999	27-140		[84]
British Isles	2001	85-100 (31-310)		[84]
Toronto, Canada	2001	7-84		[84]
Toronto, Canada	2001	31-78		[84]
India and Pakistan	2006 and 2011	4.9-140	Tri- and Tetra-CNs	[97]
East China	2012-2015	5.9-143	Tri-CNs	[94]
Northern Taiwan	2017	172 ± 111	Tri- and Tetra-CNs	[100]
Dalian, China	2022	0.05-0.43 (summer) 0.08 -1.42 (winter)	Tetra- and Hexa-CNs	[144]

PCNs: Polychlorinated naphthalenes; CNs: chloronaphthalenes.

Table 6. PCNs concentrations in sediment samples in different countries

Country	Concentration (ng/g dw)	Dominant homologue	Sampling year	Ref.
Liaohe River Basin, China	0.33-12.5	Tri-CNs and tetra-CNs	2010	[145]
East China	0.60-4600	Octa-CN	2009	[118]
North China	0.12-5.10	Tri- to Penta-CNs	2009	[146]
Lake Ontario	21-38	Hexa- to Octa-CNs		[81]
Barcelona (Spain)	0.17-3.27	Tetra-CNs	2003	[147]
Pakistan	8.94-414	Tri- to Penta-CNs	2012	[103]
Italy	ND- 0.053	Tri- to Penta-CNs	1995	[103]
Baltic sea, Sweden	0.27-2.8	Tetra-CNs	1991-1993	[78]
Qingdao, China	212-1209	Tri-, Tetra- and Penta-CNs	1997 and 1999	[148]
Taiwan	0.012-0.055 (reservoir) 0.408-1.47 (river)	Tetra- to Penta-CNs	2017	[108]

PCNs: Polychlorinated naphthalenes; CNs: chloronaphthalenes.

humans[17]. Recently, Zacs *et al.*[13] analysed PCNs concentrations in 15 fish samples from Latvia, and the highest ∑PCN concentration of 45.7 pg/g was detected. The obtained results were in general agreement with the POP-like properties of PCNs and other studies on PCNs occurrence in food. The result also indicated that aquatic biota had been subjected to PCNs bioaccumulation from historically used technical PCN formulations or from industrial emissions[17].

Kim *et al.*[109] reported PCNs concentrations in Crucian Carp obtained from upstream and midstream rivers in South Korea. PCNs concentrations ranged from 1.46-3.08 pg/g ww, 20.6-31.6 pg/g ww, 14.8-40.7 pg/g ww and 7.57-18.0 pg/g in muscles, livers, gonads and blood of Crucian Carp, respectively. However, the PCNs concentrations in muscle and liver tissues were lower than those reported in previous studies[110-112]. Penta-CNs were dominant in both muscles and gonads, constituting 55.6% and 39.8%, respectively, similar to the results from previous studies on various fish samples[81,108,113,114]. Zhihua *et al.*[115] also analysed PCNs concentrations in 75 different fish species from UK, Ireland and France. PCNs concentrations observed

ranged from 0.7-265 ng/kg ww, with the highest mean concentrations recorded at 67 ng/kg ww and 68 ng/kg ww for Sardine and Mackerel, respectively. Though similar findings were obtained in other studies, Fernandes *et al.*[116] and Zhihua *et al.*[115] pointed out that size, age and seasonal changes may also have influenced the findings. Additionally, higher concentrations were observed for penta- and hexa-CNs (PCNs 52, 53 and 66/67). McGoldrick *et al.*[18] determined PCNs concentrations in Trout and Walleye samples collected from 11 locations in the Canadian Great Lakes. Across the Great Lakes, ∑PCNs concentrations ranged from 171-7660 pg/g ww, and Penta-CNs were the most predominant congeners[18].

Soil and dust

Niu*et al.*[117] determined PCNs concentrations in the soil from WEEE recycling sites in Nanyang, Shanglian, Huamei, Longmen, and Yaocuowei) of Southeast China. The total concentrations of $\sum_{18}$PCN congeners differed considerably from one location to another, with concentration range covering three orders of magnitude from 1.22-4.00 × 10^3 ng/g dw. Overall, the frequencies of detection of tetra-, hexa-, and penta-CNs congeners were 85%, 79%, and 52%, respectively. The mono-, di-, and tri-CNs congeners were detected at > 90% in soil samples, but at relatively low concentrations (N.D. to 350 ng/g). In comparison with other similar studies, the observed congener profiles in the aforementioned study were different from those observed in the natural environment[99,118]. The observed profile indicated differences in potential sources of PCNs in e-waste recycling areas and natural areas. Waheed *et al.*[43] collected 250 indoor dust samples from five major e-waste hubs in Pakistan. PCNs concentrations in overall indoor dust samples ranged from 0.25-697 ng/g, with tetra-CNs (38%) and tri-CNs (26%) being the most dominant congeners[43]. Compared with other studies, PCNs concentrations in soil samples revealed a similar pattern of the tetra- and tri- CNs congeners' dominancy in Pakistan, China, Ghana and other countries[39,95,104,119-122].

Eggs

Vorkamp *et al.*[123] determined PCNs concentrations in addled eggs collected during field studies on the South Greenland peregrine falcon in Denmark[123]. The ΣPCN levels in the eggs of peregrine falcon were 21 ng/g lipid weight (lw). This level is considered high for PCNs in bird eggs compared to other studies[12,124-126]. Another study by McGoldrick *et al.*[18] analysed PCNs concentrations in Herring Gull (*Larus argentatus*) eggs, which were collected annually as part of the Great Lakes Herring Gull Contamination Monitoring Program in April-May[18]. The highest PCNs concentrations were detected at 3020 pg/g ww in eggs from the colony on Middle Island, and the most abundant PCNs congener was hexa-CNs, which comprised 39-79% of the ∑PCNs measured.

Consumer Products

In Japan, Yamamoto *et al.*[127] conducted a preliminary study to monitor PCNs in waste. PCNs were detected at 36,000 mg/kg in Neoprene FB samples and 97-2000 mg/kg in rubber printer belts[127]. Additionally, levels of PCNs in refuse derived fuel and automotive shredder residues were 0.01-0.086 mg/kg[128]. In addition to the provided information on the levels of PCNs in consumer products, Table 7 summarizes levels of PCNs or PCBs in selected applications and some waste fractions.

Humans

Human exposure to PCNs can occur via oral, inhalation and dermal routes. However, dietary intake is the most significant route of exposure for the general population[17]. Despite the scarcity of data on the occurrence of PCNs in human tissues, several studies from Japan, Canada, Sweden, Russia, Kazachstan and Germany showed PCNs levels in blood, breast milk, adipose tissue and liver[129-133]. Studies have further indicated that human milk is considered one of the core monitoring matrices of the United Nations Environmental Programme' on POPs monitoring programme focusing on testing the efficiency of executing the Stockholm Convention[23].

Table 7. Concentrations of PCNs (or PCBs)* in selected applications and some waste fractions

Product/sample	POPs measured	PCNs or PCBs content (mg/kg)	Ref.
Neoprene rubber	PCNs	36,000-45,000	[7,127]
Rubber coated plastic	PCNs	1000	[7]
Rubber belt for printers	PCNs	41-2000 (3/21)	[127]
Rubber belt for printers	PCNs	0.001-0.1 (17/21)	[127]
Aerosol adhesives	PCNs	1150-1200	[7]
Sealants	PCBs*	28,00 -224,000	[128]
Paints	PCBs*	30,000 -160,000	[149]
Cable sheathing and coating	PCBs	30,000-200,000	[150]
Automotive shredder residue	PCNs	0.026-0.040	[127]
Refused derive fuel	PCNs	0.011-0.086	[127]
PCN-technical mixture	PCNs	930,000-1,000,000	[7]
Transformer oils	Askarel PCB*	ca. 600,000**	[150]
Contaminated transformer oil	PCB*	50 - 100,000	[150]
Capacitor/condensers	PCB*	ca. 600,000**	[150]
Transformer oils	unintentional PCNs	1000-9000	[15]
Automotive shredder residue	PCNs	0.026-0.040	[127]
Refused derive fuel	PCNs	0.011-0.086	[127]

*For these applications, only PCB data were available. Due to the use in the same application and similar chemical properties, the levels of PCBs used might reflect if PCNs were/are used; **The PCBs are normally mixed with ca. 300,000 mg/kg PCBs. PCNs: Polychlorinated naphthalenes; PCBs: polychlorinated biphenyl; POPs: persistent organic pollutants.

Human diet

Recently, Zac *et al.*[13] determined PCNs in food products from Latvia. The following selected food products, milk, meat, eggs, fish, cod liver, bread and cereal, vegetable oils, fish oil and baby food were analyzed. The highest ∑PCN concentration detected was 45.7 pg/g in fish samples, which reflected the exposure of aquatic biota to PCNs bioaccumulation from the historical use of technical PCN formulations. Other types of food products also showed a wide range of PCN levels. However, there was less contamination observed in the following order of mean ∑PCN concentrations: bread - 9.49 pg/g; dairy products - 5.29 pg/g; vegetable oil - 3.53 pg/g; meat - 3.13 pg/g; baby food - 1.40 pg/g; eggs - 1.14 pg/g. The observed PCNs concentrations in the selected foods were broadly similar to those reported from other countries[20,21,50,77-88,115-117,125-127,134,135]. In addition to the provided data, Table 8 summarizes concentrations of PCNs in the human diet.

Breast milk and serum

Li *et al.*[136] analysed levels of PCNs in Chinese human milk, which ranged from 164.4-2497.4 pg/g lw with the mean and median of 514.3 pg/g lw and 382.4 pg/g lw, respectively. In comparison with other studies, the concentration of PCNs in human milk was about 4 to 5 magnitude higher than the PCDD/Fs and one order of magnitude lower than dioxin-like PCBs reported by Zhang *et al.*[137]. Li *et al.*[23] analysed 3790 human milk samples in 2017-2019 from 77 cities around China. PCNs were present in the pooled samples that were analysed. The obtained results were compared with the available data on PCNs levels in human samples. PCNs levels were lower than the levels in adipose tissue samples from some developed countries[130,132,133]. PCNs concentrations in human blood samples from Korea were comparable to the ones obtained by Li *et al.*[23] but higher in blood samples from an industrial site in China[24,132]. Another recent study determined PCNs concentrations in workers, children and residents within the vicinity of an electronic waste site[43]. PCNs concentrations in workers, children and residents ranged from 1.12-401 pg/g lipid, 0.25-302 pg/g lipid and 0.15-313 pg/g lipid, respectively. Moreover, the highest ∑PCN concentration was recorded in workers, followed by residents and children with tetra- and penta-CNs as the dominant congeners, reflecting

Table 8. A summary of PCNs studies in food

Country	Type of sample	Sampling year	Quantitation type	PCNs concentrations (ng/kg)	Ref.
Great Lakes & inland Michigan. N America	Fish	1996-1997	Homologue totals tri-octa	19-31,400	[77]
Catalonia, Spain	Fish	2000	Total congener tetra-octa	39 (average)	[151]
Baltic sea	Fish	2001-2003	Sum of 16, tetra-octa congeners	1-190	[152]
Baltic sea	Fish	2001-2003	Sum of 16, tetra- octa congeners	20-450	[152]
Remote lakes, Finland	Fish	2001-2003	Sum of 16, tetra-octa congeners	2-66	[152]
East & South China sea	Fish	2003-2004	Homologue totals tri-octa	137-545 (lipid wt, average	[153]
Catalonia, Spain	Fish	2005	Homologue totals tetra- octa	13-227	[76]
Catalonia, Spain	Fish	2006	Homologue totals tetra	12.8-226.9	[154]
China	Fish	2006	Homologue totals congeners	25-640 (lipid wt, average)	[155]
United Kingdom	Fish	2007	Sum of 12 penta-octa congeners	0.73-37.3	[156]
Ireland	Fish	2007-2008	Sum of 12, penta-octa congeners	2.08-59.3	[157]
Scotland	Fish	2008	Sum of 12, penta-octa	0.3-63	[116]
Scotland	Fish	2008	Sum of 12, penta-octa congeners	2.5-103	[116]
United Kingdom fresh waters	Fish	2008-2009	Sum of 12, penta-octa congeners	0.7-265	[158]
United Kingdom marine waters	Fish	2013-2014	Sum of 12, penta-octa congenersSum of 12, penta-octa congeners	0.7-265	[159]
Latvia	Fish	2019-2020	26 PCN congeners, tetra-octa congeners	45.7	[13]
East & South China sea	Shell fish	2003-2004	Homologue totals tri-octa	94-1300 (lipid wt, average)	[153]
Ireland	Shell fish	2007-2008	Sum of 12, penta-octa congeners	0.18-2.34	[157]
Shanghai, China	Crab	2019	Di-hepta congeners	5.46-43.8 ww	[160]
Shanghai, China	Feed	2019	Tri-octa congeners	20.1-758 WW 30.3-92.6 ww	[160]
Catalonia, Spain	Eggs	2000	Homologue totals tetra-octa	23 (average)	[151]
Catalonia, Spain	Eggs	2006	Homologue totals tetra-octa	1.7-4.3	[154]
China	Eggs	2006	Total congeners	43.8 (lipid wt., average)	[155]
Ireland	Eggs	2007-2008	Sum of 12, penta-octa congeners	0.23-2.22	[157]
Latvia	Eggs	2019-2020	26 PCN congeners, tetra-octa congeners	1.14	[13]
Catalonia, Spain	Milk	2000	Homologue totals tetra- octa	0.4 (average)	[157]
Catalonia, Spain	Milk	2006	Homologue totals tetra- octa	0.5-1.2	[151]
Ireland	Milk	2007-2008	Sum of 12, penta-octa congeners	0.09-0.38	[154]
North China	Raw cow milk	2019-2020	Mono-octa-CNs	89.6-2050	[161]
Catalonia, Spain	Dairy food	2000	Homologue totals tetra- octa	36 (average)	[151]
Catalonia, Spain	Dairy food	2006	Homologue totals tetra- octa	0.8-22.7	[154]
United Kingdom	Dairy food	2007	Sum of 12, penta- octa congeners	0.52-6.09	[156]
Ireland	Dairy food	2007-2008	Sum of 12, penta- octa congeners	0.68-3.13	[157]
China	Dairy food	-	-	5.6-103 (cheese) 5.0-199 (butter)	[162]
Latvia	Dairy food	2019-2020	26° PCN congeners, tetra-octa congeners	5.9	[13]
Catalonia, Spain	Meat	2000	Homologue totals tetra-octa	18 (average)	[151]
Catalonia, Spain	Meat	2006	Homologue totals tetra-octa	1.8-5.8	[154]
United Kingdom	Meat	2007	Sum of 12, penta-octa congeners	0.19-5.69	[156]
Tibet-Qinghai Plateau, China	Meat	2007	Tri-octa individual congeners	13.6	[163]
Catalonia, Spain	Cereals & bread	2000	Homologue totals tetra- octa	3-71 (average)	[151]
Catalonia, Spain	Cereals &	2006	Homologue totals tetra- octa	5.3-15.1	[154]

	bread				
United Kingdom	Cereals & bread	2007	Sum of 12, penta-octa congeners	0.28	[156]
Ireland	Cereals & bread	2007-2008	Sum of 12, penta-octa congeners	0.25-0.77	[157]
Catalonia, Spain	Fruits & vegetables	2000	Homologue totals tetra-octa	0.7-4 (average	[151]
Catalonia, Spain	Fruits & vegetables	2006	Homologue totals tetra-octa	0.9-3.9	[154]
Ireland	Fruits & vegetables	2007	Sum of 12, penta-octa congeners	0.16-2.84	[157]
United Kingdom	Fruits & vegetables	2007	Sum of 12, penta-octa congeners	0.15-0.16	[156]

PCNs: Polychlorinated naphthalenes.

exposure time, intensity and distance from the e-waste sites. Comparing the obtained data with previous studies, penta-, hexa- and tetra- CNs congeners were reported as predominant congeners detected in human plasma, liver, milk and fat tissue[64,133,138]. Penta- and hexa-CNs and, to a lesser extent, tetra-CNs congeners were the most prevalent observed in human tissue samples, showing some consistency with the normally observed profiles in animal tissues[3].

PCNS STUDIES IN AFRICA

According to the UNDP, Africa covers over 30 million km^2, including over 54 countries and a population of about 1.17 billion people[137]. However, it remains the least studied continent in the world with respect to PCNs studies in different matrices. In fact, only three studies on PCNs have been published in different matrices[3,10,42]. Jaward *et al.*[42] analysed 55 air samples for PCNs along the north to south Atlantic transect in 2001, as the Pelagia traveled from the Netherlands (1.06° N, 1.43° E) to South Africa (33.88° S, 18.3° E). The reported mean PCN concentrations ranged between 0.3-86 pg/m^3. The European samples exhibited the highest levels. However, fairly high values were also detected off the West African coast, as well as in samples taken closest to South Africa. Jaward *et al.*[42]. further reported that there are limited data on regional or global usage and emission of PCNs. However, emissions from halowaxes and high-temperature combustion processes were identified as the major sources. Additionally, although inventories have been developed for Europe, almost no data are available for Africa[42]. Another study determined the levels of atmospheric POPs in Ghana between May and July 2010[10]. PCNs levels averaged 49 ± 5.4 pg/m^{3,} with a high impact on the southern coastal zone of Ghana, where uncontrolled open burning of electronic waste, industrial emissions, and harbour environment were identified among possible emission factors. Tri- and tetra-CNs were the most abundant congeners, altogether constituting approximately 90% of total PCN homologues composition[10]. It was concluded that the study brought to the fore the emerging problems of the occurrence of organohalogens in matrices that might be facing African nations like Ghana[10]. Agunbiade *et al.*[3] reviewed data on the occurrence and analytical procedures for the evaluation of PCNs in human and environmental matrices in South Africa. The study was conducted as a result of PCNs being listed as POPs at the Stockholm Convention in May 2015. It was reported that highly toxic congeners (CNs 66, 67 and 73) are prevalent in most samples; thus, there is a need for continuous monitoring in our environment[3]. In comparison with the reviewed PCNs studies from other continents, very little has been done with regard to PCNs studies in Africa. There is an urgent need to conduct more research studies in the different matrices such as atmosphere, river, sediments, soil, indoor dust, biota, consumer products, landfills, human diet, blood and serum in order to cover this huge omission. Africa then becomes an important study area for PCNs studies.

RESEARCH GAPS PRIORITIES ON PCNS STUDIES IN AFRICA

Matrices to be prioritized

Among the different matrices, Akinrinade *et al.*[139] pointed out that the atmosphere is particularly an important matrix to be prioritized and monitored for POPs since it is the key route via which contaminants are distributed over long distances beyond the original source of emission. Again, with the high temperatures in the African content, volatilisation of POPs from both primary and secondary sources will be more facile. Consequently, the atmosphere may become a proportionally greater reservoir of POPs in the continent[140]. Marek *et al.*[141] and Wemken *et al.*[142] pointed out that the contribution to overall human exposure to POPs in Europe and North America from outdoor air is minor. In contrast, greater emissions of POPs into the atmosphere may arise in many parts of Africa due to factors including poor handling of waste materials and weak environmental laws enforcement, leading to open waste dumping and burning of waste materials[139]. In 2001, Jaward *et al.*[42] detected elevated levels of PCNs in the atmosphere from locations off the coasts of West and South Africa. Although precise sources were not fully resolved, these pollutants might have emanated from countries bordering the west and south coasts of Africa[10]. These may have been as results of combustion or from toxic wastes exported to the continent[10]. Both issues constitute grave environmental challenges on the continent. For instance, a substantial amount of MSW generated in the African continent is burnt uncontrollably in the open at waste dumpsites, as incineration and proper landfill facilities are lacking. Putrescible fractions, plastics, metals, papers, *etc.* in the waste stream are all burnt together. Potentially, this could release unintentional POPs into the atmosphere[10,29,31,143]. Although sources of PCNs in the African continent are not well documented, presumably, there are potential hotspots of PCNs emissions in certain African countries that should be investigated. Since the atmosphere is a key vector through which contaminants are distributed over long distances, the occurrence of PCNs in other matrices such as rivers, sediments, soil, indoor dust, biota, consumer products, landfills, human diet, blood and serum becomes obvious. It is, therefore, crucial to prioritize the monitoring and investigation of the occurrence of PCNs not only in consumer products, landfill leachate and sediments but also in other different matrices.

Research gaps direction

While studies on POPs are emerging in Africa, it is, however, noteworthy that very few studies on PCNs in various matrices have been conducted. To date, only three studies on PCNs have been published[3,10,42]. Nonetheless, despite the scarcity of published data on environmental contamination with PCNs in Africa, about 163 studies on PCN levels in different environmental departments in Asia, Europe and America have been published. Given the large African population, increasing industrialization, urbanization and the increasing demand for imported goods, this is an important omission. In addition, information about environmental levels of PCNs in Africa is essential for guiding efforts to reduce health implications associated with the contaminant in order to achieve the United Nations' Sustainable Development Goals on healthy lives and the promotion of well-being for all at all ages by 2030. There is, therefore, a critical need to study environmental concentrations of PCNs in Africa as well as to expand sampling sites to include landfill leachates, consumer goods and other matrices. Historical sources, current sources, as well as Africa's characteristics, prevailing global warming, make Africa an important study area. In Africa, there are need to assess the presence, use and lifecycle of PCNs in the continent, as well as to develop a National Implementation Plan with specific activities in order to develop PCNs inventories. In view of the effects of PCNs globally, their use needs to be legally restricted or banned. Robust PCNs inventories are overdue in Africa and, therefore, require some attention. It is, therefore, important to gather comparable data on concentrations of PCNs in consumer products and other matrices in all the continents in order to have a global overview of the state PCNs. It is also crucial to study PCNs in Africa in order to understand the impacts of the Stockholm Convention to reduce POPs in Africa and assess their distribution and influence on other continents on the environmental burden of PCNs in Africa, and vice versa.

CONCLUSION

From the few PCNs studies conducted in Africa, it can be concluded that not much is known about the environmental pollution effects of these pollutants on the African continent. Further research studies on levels of PCNs in matrices can assist in addressing these research gaps. Thus, the expansion of sampling sites not only includes landfill leachates, sediments and consumer goods but also other matrices such as atmosphere, rivers, sediments, soil, indoor dust, biota, human diet, blood and serum, should be prioritized. The effect of temperature on the emission of PCNs has been observed to be very important. Considering the fact that the African continent experiences high temperatures, any increase in temperature coupled with global warming will directly lead to enhanced volatilization of PCNs from their sources, thereby exposing a large population. In addition, foodstuffs imported from other countries might be another pathway for Africa's exposure to PCNs. Currently, there is no published information on the production, use and regulations of PCNs in Africa. Considering the global effects of PCNs, their use should be strictly controlled with robust PCNs inventories developed in Africa. It is also important to collate comparable data globally on concentrations of PCNs in a wider number of matrices in order to have a global overview of PCN distribution. It is of paramount importance to study PCNs in Africa so that a better understanding of the impacts of the Stockholm Convention to reduce POPs in Africa can be achieved; and to assess their distribution, influence on other continents on the environmental burden of PCNs in Africa, and vice-versa.

DECLARATIONS

Acknowledgements

The authors are very grateful to the Tshwane University of Technology (TUT) and the National Research Foundation (NRF) for the grants provided for this research.

Author's contribution

Prepared the draft manuscript: Nevondo V
Edited and proofed read the manuscript before submission for consideration for publication: Okonkwo JO
All authors read and approved the final manuscript.

Available data and materials

Not applicable.

Financial support and sponsorship

This study was funded by Tshwane University of Technology (TUT) and the National Research Foundation (NRF).

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Copyright

© The Author(s) 2022.

REFERENCES

1. Gevao B, Harner T, Jones KC. Sedimentary record of polychlorinated naphthalene concentrations and deposition fluxes in a dated lake core. *Environ Sci Technol* 2000;34:33-8. DOI
2. Falandysz J, Rappe C. Specific pattern of tetrachloronaphthalenes in black cormorant. *Chemosphere* 1997;35:1737-46. DOI
3. Agunbiade IV, Adeniji AO, Okoh AI, Okoh OO. A review on occurrence and analytical procedures for the evaluation of polychlorinated naphthalenes in human and environmental matrices. *Environ Pollut Bioavailability* 2020;32:154-74. DOI
4. Brinkman U, Reymer H. Polychlorinated naphthalenes. *J Chromatogr* 1976;127:203-43. DOI PubMed
5. Kucklick JR, Helm PA. Advances in the environmental analysis of polychlorinated naphthalenes and toxaphene. *Anal Bioanal Chem* 2006;386:819-36. DOI PubMed
6. Falandysz J. Polychlorinated naphthalenes: an environmental update. *Environmental Pollution* 1998;101:77-90. DOI PubMed
7. Yamashita N, Taniyasu S, Hanari N, Horii Y, Falandysz J. Polychlorinated naphthalene contamination of some recently manufactured industrial products and commercial goods in Japan. *J Environ Sci Health A Tox Hazard Subst Environ Eng* 2003;38:1745-59. DOI PubMed
8. Falandysz J, Fernandes A, Gregoraszczuk E, Rose M. The toxicological effects of halogenated naphthalenes: a review of aryl hydrocarbon receptor-mediated (dioxin-like) relative potency factors. *J Environ Sci Health Part C* 2014;32:239-72. DOI PubMed
9. UNEP. (United Nations Environmental Programme). Draft guidance on preparing Inventories of polychlorinated naphthalenes (PCN) listed under the stockholm convention on POPs. Available from: http://chm.pops.int/Implementation/NationalImplementationPlans/GuidanceArchive/NewlyDevelopedGuidance/GuidanceforPCN/tabid/6231/Default.aspx [Last accessed on 11 Apr 2022].
10. Hogarh JN, Seike N, Kobara Y, Masunaga S. Atmospheric polychlorinated naphthalenes in Ghana. *Environ Sci Technol* 2012;46:2600-6. DOI PubMed
11. Babayemi JO, Nnorom IC, Osibanjo O, Weber R. Ensuring sustainability in plastics use in Africa: consumption, waste generation, and projections. *Environ Sci Eur* 2019:31. DOI
12. Bidleman TF, Helm PA, Braune BM, Gabrielsen GW. Polychlorinated naphthalenes in polar environments--a review. *Sci Total Environ* 2010;408:2919-35. DOI PubMed
13. Zacs D, Perkons I, Pasecnaja E, Bartkevics V. Polychlorinated naphthalenes (PCNs) in food products in Latvia: congener-specific analysis, occurrence, and dietary exposure of the general population. *Chemosphere* 2021;264:128460. DOI PubMed
14. Liu G, Cai Z, Zheng M. Sources of unintentionally produced polychlorinated naphthalenes. *Chemosphere* 2014;94:1-12. DOI PubMed
15. Yamashita N, Kannan K, Imagawa T, Miyazaki A, Giesy JP. Concentrations and profiles of polychlorinated naphthalene congeners in eighteen technical polychlorinated biphenyl preparations. *Environ Sci Technol* 2000;34:4236-41. DOI
16. Hou S, Dlugogorski BZ, Mackie JC, et al. Oxidation of 4-bromo-4'-chlorobiphenyl, model species for forming mixed halogenated aromatic compounds. *IJEP* 2017;61:243. DOI
17. Fernandes A, Rose M, Falandysz J. Polychlorinated naphthalenes (PCNs) in food and humans. *Environ Int* 2017;104:1-13. DOI PubMed
18. McGoldrick DJ, Pelletier M, de Solla SR, Marvin CH, Martin PA. Legacy of legacies: chlorinated naphthalenes in lake trout, walleye, herring gull eggs and sediments from the Laurentian great lakes indicate possible resuspension during contaminated sediment remediation. *Sci Total Environ* 2018;634:1424-34. DOI PubMed
19. Han Y, Liu W, Li H, et al. Distribution of polychlorinated naphthalenes (PCNs) in the whole blood of typical meat animals. *J Environ Sci (China)* 2018;72:208-12. DOI PubMed
20. Blankenship AL, Kannan K, Villalobos SA, et al. Relative potencies of individual polychlorinated naphthalenes and halowax mixtures to induce ah receptor-mediated responses. *Environ Sci Technol* 2000;34:3153-8. DOI
21. Villeneuve DL, Kannan K, Khim JS, et al. Relative potencies of individual polychlorinated naphthalenes to induce dioxin-like responses in fish and mammalian in vitro bioassays. *Arch Environ Contam Toxicol* 2000;39:273-81. DOI PubMed
22. Johnson-Restrepo B, Kannan K, Rapaport DP, Rodan BD. Polybrominated diphenyl ethers and polychlorinated biphenyls in human adipose tissue from New York. *Environ Sci Technol* 2005;39:5177-82. DOI PubMed
23. Li C, Zhang L, Li J, et al. Polychlorinated naphthalenes in human milk: Health risk assessment to nursing infants and source analysis. *Environ Int* 2020;136:105436. DOI PubMed
24. Park H, Kang JH, Baek SY, Chang YS. Relative importance of polychlorinated naphthalenes compared to dioxins, and polychlorinated biphenyls in human serum from Korea: contribution to TEQs and potential sources. *Environ Pollut* 2010;158:1420-7. DOI PubMed
25. Sulfonate P. Canadian environmental protection Act, 1999. Available from: https://www.canada.ca/content/dam/eccc/documents/pdf/pded/feqg-pfos/20180606-PFOS-EN.pdf [Last accessed on 11 Apr 2022].
26. Arinaitwe K, Muir DC, Kiremire BT, et al. Polybrominated diphenyl ethers and alternative flame retardants in air and precipitation samples from the northern Lake Victoria region, East Africa. *Environ Sci Technol* 2014;48:1458-66. DOI PubMed
27. Asante KA, Adu-Kumi S, Nakahiro K, et al. Human exposure to PCBs, PBDEs and HBCDs in Ghana: temporal variation, sources of exposure and estimation of daily intakes by infants. *Environ Int* 2011;37:921-8. DOI PubMed
28. Batterman S, Chernyak S, Gouden Y, et al. PCBs in air, soil and milk in industrialized and urban areas of KwaZulu-Natal, South Africa. *Environ Pollut* 2009;157:654-63. DOI PubMed PMC
29. Babayemi J, Sindiku O, Osibanjo O, Weber R. Substance flow analysis of polybrominated diphenyl ethers in plastic from

EEE/WEEE in Nigeria in the frame of Stockholm Convention as a basis for policy advice. *Environ Sci Pollut Res Int* 2015;22:14502-14. DOI PubMed

30. Odusanya DO, Okonkwo JO, Botha B. Polybrominated diphenyl ethers (PBDEs) in leachates from selected landfill sites in South Africa. *Waste Manag* 2009;29:96-102. DOI PubMed
31. Oloruntoba K, Sindiku O, Osibanjo O, Balan S, Weber R. Polybrominated diphenyl ethers (PBDEs) in chicken eggs and cow milk around municipal dumpsites in Abuja, Nigeria. *Ecotoxicol Environ Saf* 2019;179:282-9. DOI PubMed
32. Sindiku O, Babayemi J, Osibanjo O, et al. Polybrominated diphenyl ethers listed as Stockholm Convention POPs, other brominated flame retardants and heavy metals in e-waste polymers in Nigeria. *Environ Sci Pollut Res Int* 2015;22:14489-501. DOI PubMed
33. Mansour SA. Persistent organic pollutants (POPs) in Africa: Egyptian scenario. *Hum Exp Toxicol* 2009;28:531-66. DOI PubMed
34. Folarin BT, Abdallah MA, Oluseyi T, Olayinka K, Harrad S. Concentrations of polychlorinated biphenyls in soil and indoor dust associated with electricity generation facilities in Lagos, Nigeria. *Chemosphere* 2018;207:620-5. DOI PubMed
35. Nkabinde SN, Okonkwo JO, Olukunle OI, Daso AP. Determination of legacy and novel brominated flame retardants in dust from end of life office equipment and furniture from Pretoria, South Africa. *Sci Total Environ* 2018;622-623:275-81. DOI PubMed
36. Vaccher V, Ingenbleek L, Adegboye A, et al. Levels of persistent organic pollutants (POPs) in foods from the first regional Sub-Saharan Africa Total Diet Study. *Environ Int* 2020;135:105413. DOI PubMed
37. Katima Z, Okonkwo JO, Daso AP. A review of brominated flame retardants in the environment with emphasis on atmospheric levels, knowledge and information gaps in the African continent. *Atmospheric Pollution Research* 2017;8:767-80. DOI
38. Sibiya I, Poma G, Cuykx M, et al. Targeted and non-target screening of persistent organic pollutants and organophosphorus flame retardants in leachate and sediment from landfill sites in Gauteng Province, South Africa. *Sci Total Environ* 2019;653:1231-9. DOI PubMed
39. Jaward FM, Zhang G, Nam JJ, et al. Passive air sampling of polychlorinated biphenyls, organochlorine compounds, and polybrominated diphenyl ethers across Asia. *Environ Sci Technol* 2005;39:8638-45. DOI PubMed
40. Adu-Kumi-Jonathan J, Akortia HE, Bell G, Di Gangi J. Persistent organic pollutants (POPs) in eggs: report from Africa. Available from: https://arnika.org/en/publications/persitent-organic-pollutants-in-eggs-report-for-africa [Last accessed on 11 Apr 2022].
41. Brits M, de Boer J, Rohwer ER, et al. Short-, medium-, and long-chain chlorinated paraffins in South African indoor dust and cat hair. *Chemosphere* 2020;238:124643. DOI PubMed
42. Jaward FM, Barber JL, Booij K, Jones KC. Spatial distribution of atmospheric PAHs and PCNs along a north-south Atlantic transect. *Environ Pollut* 2004;132:173-81. DOI PubMed
43. Waheed S, Khan MU, Sweetman AJ, et al. Exposure of polychlorinated naphthalenes (PCNs) to Pakistani populations via non-dietary sources from neglected e-waste hubs: A problem of high health concern. *Environ Pollut* 2020;259:113838. DOI PubMed
44. Iqbal M, Breivik K, Syed JH, et al. Emerging issue of e-waste in Pakistan: A review of status, research needs and data gaps. *Environ Pollut* 2015;207:308-18. DOI PubMed
45. Jakobsson E, Asplund L. Polychlorinated naphthalenes (PCNs). Berlin: Springer Berlin Heidelberg;2000. p. 97-126. DOI
46. UNITED NATIONS. Further assessment of persistent organic pollutants (POPs). Available from: https://unece.org/fileadmin/DAM/env/documents/2002/eb/wg5/eb.air.wg.5.2002.2.e.pdf [Last accessed on 11 Apr 2022].
47. Kannan K, Imagawa T, Blankenship AL, Giesy JP. Isomer-Specific Analysis and toxic evaluation of polychlorinated naphthalenes in soil, sediment, and biota collected near the site of a former chlor-alkali plant. *Environ Sci Technol* 1998;32:2507-14. DOI
48. Howe PD, Melber C, Kielhorn J, Mangelsdorf I, Organization WH. Chlorinated naphthalenes: World Health Organization; 2001. DOI
49. Rose M, Falandysz J. Emerging POPs. A special session at "Dioxin 2008" in Birmingham. *Rocz Panstw Zakl Hig* 2008;59:473-81,483. PubMed
50. Hayward D. Identification of bioaccumulating polychlorinated naphthalenes and their toxicological significance. *Environ Res* 1998;76:1-18. DOI PubMed
51. . Japan ministry of economy, trade and industry, chemical council safety guideline chapter. The regulation of polychlorinated naphthalenes and hexachlorobenzene.
52. UNEP (United Nations Environmental Programme). Draft risk management evaluation: chlorinated naphthalenes. Available from: https://www.informea.org/en/draft-risk-management-evaluation-chlorinated-naphthalenes [Last accessed on 11 Apr 2022].
53. Nevondo V, Okonkwo OJ. Status of short-chain chlorinated paraffins in matrices and research gap priorities in Africa: a review. *Environ Sci Pollut Res Int* 2021;28:52844-61. DOI PubMed PMC
54. Helm PA, Kannan K, Bidleman TF. Polychlorinated Naphthalenes in the Great Lakes. *Persistent Organic Pollutants in the Great Lakes* :2006. p. 267-306. DOI
55. Potrykus A, Milunov M, Weißenbacher J. Identification of potentially POP-containing Wastes and Recyclates-Derivation of Limit Values. Available from: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_35_2015_identification_of_potentially_pop-containing_wastes.pdf [Last accessed on 11 Apr 2022].
56. ESWI. Study on waste related issues of newly listed POPs and candidate POPs. Available from: https://op.europa.eu/en/publication-detail/-/publication/ad438122-39ee-49d3-a771-a98cad48a20a [Last accessed on 11 Apr 2022].
57. Yamamoto T, Noma Y, Sakai SI. Thermal destruction of wastes containing polychlorinated naphthalenes in an industrial waste incinerator. *Environ Sci Pollut Res Int* 2018;25:31819-27. DOI PubMed

58. Helm PA, Bidleman TF. Current combustion-related sources contribute to polychlorinated naphthalene and dioxin-like polychlorinated biphenyl levels and profiles in air in Toronto, Canada. *Environ Sci Technol* 2003;37:1075-82. DOI PubMed
59. Lee RG, Coleman P, Jones JL, Jones KC, Lohmann R. Emission factors and importance of PCDD/Fs, PCBs, PCNs, PAHs and PM10 from the domestic burning of coal and wood in the U.K. *Environ Sci Technol* 2005;39:1436-47. DOI PubMed
60. Meijer SN, Harner T, Helm PA, et al. Polychlorinated naphthalenes in U.K. soils: time trends, markers of source, and equilibrium status. *Environ Sci Technol* 2001;35:4205-13. DOI PubMed
61. Pan J, Yang Y, Taniyasu S, et al. Comparison of historical record of PCDD/Fs, dioxin-like PCBs, and PCNs in sediment cores from Jiaozhou Bay and coastal Yellow Sea: implication of different sources. *Bull Environ Contam Toxicol* 2012;89:1240-6. DOI PubMed
62. Takasuga T, Inoue T, Ohi E, Kumar KS. Formation of polychlorinated naphthalenes, dibenzo-p-dioxins, dibenzofurans, biphenyls, and organochlorine pesticides in thermal processes and their occurrence in ambient air. *Arch Environ Contam Toxicol* 2004;46:419-31. DOI PubMed
63. Liu G, Zheng M, Du B, et al. Identification and characterization of the atmospheric emission of polychlorinated naphthalenes from electric arc furnaces. *Environ Sci Pollut Res Int* 2012;19:3645-50. DOI PubMed
64. Jiang X, Li Q, Yang L, Yang Y, Zheng M. Polychlorinated naphthalene (PCN) emissions and characteristics during different secondary copper smelting stages. *Ecotoxicol Environ Saf* 2019;184:109674. DOI PubMed
65. Liu G, Zheng M, Lv P, et al. Estimation and characterization of polychlorinated naphthalene emission from coking industries. *Environ Sci Technol* 2010;44:8156-61. DOI PubMed
66. Liu G, Zheng M, Nie Z, et al. Charactering the emission of polychlorinated naphthalenes from cement kiln. Available from: https://www.researchgate.net/publication/293156699_Charactering_the_emission_of_polychlorinated_naphthalenes_from_cement_kiln [Last accessed on 11 Apr 2022].
67. Dong S, Liu G, Zhang B, Gao L, Zheng M. Formation of polychlorinated naphthalenes during the heating of cooking oil in the presence of high amounts of sucralose. *Food Control* 2013;32:1-5. DOI
68. Ren M, Lv ZY, Xu L, et al. Partitioning and removal behaviors of PCDD/Fs, PCBs and PCNs in a modern municipal solid waste incineration system. *Sci Total Environ* 2020;735:139134. DOI PubMed
69. . Environment Canada. Sampling chemicals management plan substances from municipal solid waste landfills. Forthcoming 2022.
70. Martí I, Ventura F. Polychlorinated naphthalenes in groundwater samples from the Llobregat aquifer (Spain). *Journal of Chromatography A* 1997;786:135-44. DOI PubMed
71. Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. *Sci Adv* 2017;3:e1700782. DOI PubMed PMC
72. Rajaram S. Plastic Additives: The Global Market. Available from: https://www.bccresearch.com/market-research/plastics/plastic-additives-market-pls022b.html [Last accessed on 11 Apr 2022].
73. Hahladakis JN, Velis CA, Weber R, Iacovidou E, Purnell P. An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. *J Hazard Mater* 2018;344:179-99. DOI PubMed
74. . UNEP (United Nations Environment Programme) Plastic and toxic additives, and the circular economy: the role of the Basel and Stockholm Conventions. DOI
75. Martí-Cid R, Bocio A, Llobet JM, Domingo JL. Intake of chemical contaminants through fish and seafood consumption by children of Catalonia, Spain: health risks. *Food Chem Toxicol* 2007;45:1968-74. DOI PubMed
76. Llobet JM, Falcó G, Bocio A, Domingo JL. Human exposure to polychlorinated naphthalenes through the consumption of edible marine species. *Chemosphere* 2007;66:1107-13. DOI PubMed
77. Kannan K, Yamashita N, Imagawa T, et al. Polychlorinated naphthalenes and polychlorinated biphenyls in fishes from michigan waters including the great lakes. *Environ Sci Technol* 2000;34:566-72. DOI
78. Lundgren K, Tysklind M, Ishaq R, Broman D, van Bavel B. Polychlorinated naphthalene levels, distribution, and biomagnification in a benthic food chain in the Baltic Sea. *Environ Sci Technol* 2002;36:5005-13. DOI PubMed
79. Domingo JL. Polychlorinated naphthalenes in animal aquatic species and human exposure through the diet: a review. *J Chromatogr A* 2004;1054:327-34. DOI PubMed
80. Helm PA, Gewurtz SB, Whittle DM, Marvin CH, Fisk AT, Tomy GT. Occurrence and biomagnification of polychlorinated naphthalenes and non- and mono-ortho PCBs in Lake Ontario sediment and biota. *Environ Sci Technol* 2008;42:1024-31. DOI PubMed
81. Hanari N, Kannan K, Horii Y, et al. Polychlorinated naphthalenes and polychlorinated biphenyls in benthic organisms of a great lakes food chain. *Arch Environ Contam Toxicol* 2004;47:84-93. DOI PubMed
82. Falandysz J, Puzyn T, Szymanowska B, et al. Thermodynamic and physico-chemical descriptors of chloronaphthalenes: an attempt to select features explaining environmental behaviour and specific toxic effects of these compounds. Available from: http://www.pjoes.com/Thermodynamic-and-physico-chemical-descriptors-of-chloronaphthalenes-An-attempt-to,87377,0,2.html [Last accessed on 11 Apr 2022].
83. Suzuki G, Michinaka C, Matsukami H, Noma Y, Kajiwara N. Validity of using a relative potency factor approach for the risk management of dioxin-like polychlorinated naphthalenes. *Chemosphere* 2020;244:125448. DOI PubMed
84. Falandysz J. Chloronaphthalenes as food-chain contaminants: a review. *Food Addit Contam* 2003;20:995-1014. DOI PubMed
85. Harner T, Lee RGM, Jones KC. Polychlorinated naphthalenes in the atmosphere of the United Kingdom. *Environ Sci Technol* 2000;34:3137-42. DOI
86. Noma Y, Yamamoto T, Sakai S-I. Congener-specific composition of polychlorinated naphthalenes, coplanar PCBs, dibenzo-p-

dioxins, and dibenzofurans in the halowax series. *Environ Sci Technol* 2004;38:1675-80. DOI PubMed

87. Horii Y, Okada M, Yamashita N. Historical records of polychlorinated naphthalenes,-biphenyls,-dibenzo-P-dioxins,-dibenzofurans in a dated sediment core from Lake Kitaura, Japan. *Organohalogen Compd* 2002;57:29-32. DOI
88. Krauss M, Wilcke W. Polychlorinated naphthalenes in urban soils: analysis, concentrations, and relation to other persistent organic pollutants. *Environmental Pollution* 2003;122:75-89. DOI PubMed
89. Paatero P, Tapper U. Positive matrix factorization: a non-negative factor model with optimal utilization of error estimates of data values. *Environmetrics* 1994;5:111-26. DOI
90. Xu X, Zhang H, Chen J, et al. Six sources mainly contributing to the haze episodes and health risk assessment of $PM_{2.5}$ at Beijing suburb in winter 2016. *Ecotoxicol Environ Saf* 2018;166:146-56. DOI PubMed
91. Barbas B, de la Torre A, Sanz P, et al. Gas/particle partitioning and particle size distribution of PCDD/Fs and PCBs in urban ambient air. *Sci Total Environ* 2018;624:170-9. DOI PubMed
92. Zhu Q, Zheng M, Liu G, et al. Particle size distribution and gas-particle partitioning of polychlorinated biphenyls in the atmosphere in Beijing, China. *Environ Sci Pollut Res Int* 2017;24:1389-96. DOI PubMed
93. Wang Y, Hou H, Li H, et al. Dry and wet depositions of polychlorinated dibenzo-p-dioxins and dibenzofurans in the atmosphere in Taiwan. *Aerosol Air Qual Res* 2010;10:378-90. DOI
94. Mao S, Zhang G, Li J, et al. Occurrence and sources of PCBs, PCNs, and HCB in the atmosphere at a regional background site in east China: implications for combustion sources. *Environ Pollut* 2020;262:114267. DOI PubMed
95. Hogarh JN, Seike N, Kobara Y, et al. Passive air monitoring of PCBs and PCNs across East Asia: a comprehensive congener evaluation for source characterization. *Chemosphere* 2012;86:718-26. DOI PubMed
96. Die Q, Nie Z, Fang Y, et al. Seasonal and spatial distributions of atmospheric polychlorinated naphthalenes in Shanghai, China. *Chemosphere* 2016;144:2134-41. DOI PubMed
97. Xu Y, Li J, Chakraborty P, et al. Atmospheric polychlorinated naphthalenes (PCNs) in India and Pakistan. *Sci Total Environ* 2014;466-467:1030-6. DOI PubMed
98. Yang X, Wu J, Li M, et al. Particle size distributions and health risks of polychlorinated dibenzo-p-dioxin/furans, polychlorinated biphenyls, and polychlorinated naphthalenes in atmospheric particles around two secondary copper smelters in Shandong Province, China. *Chemosphere* 2021;269:128742. DOI PubMed
99. Xue L, Zhang L, Yan Y, Dong L, Huang Y, Li X. Concentrations and patterns of polychlorinated naphthalenes in urban air in Beijing, China. *Chemosphere* 2016;162:199-207. DOI PubMed
100. Dat ND, Chang KS, Chang MB. Characteristics of atmospheric polychlorinated naphthalenes (PCNs) collected at different sites in northern Taiwan. *Environ Pollut* 2018;237:186-95. DOI PubMed
101. Zhu Q, Zhang X, Dong S, et al. Gas and particle size distributions of polychlorinated naphthalenes in the atmosphere of Beijing, China. *Environ Pollut* 2016;212:128-34. DOI PubMed
102. Mahmood A, Malik RN, Li J, Zhang G. Congener specific analysis, spatial distribution and screening-level risk assessment of polychlorinated naphthalenes in water and sediments from two tributaries of the River Chenab, Pakistan. *Sci Total Environ* 2014;485-486:693-700. DOI PubMed
103. Espadaler I, Eljarrat E, Caixach J, Rivera J, Martí I, et al. Assessment of polychlorinated naphthalenes in aquifer samples for drinking water purposes. *Rapid Commun Mass Spectrom* 1997;11:410-4. DOI PubMed
104. Ishaq R, Persson NJ, Zebühr Y, Broman D, Naes K. PCNs, PCDD/Fs, and non-orthoPCBs, in water and bottom sediments from the industrialized Norwegian Grenlandsfjords. *Environ Sci Technol* 2009;43:3442-7. DOI PubMed
105. Cetin B, Odabasi M. Particle-phase dry deposition and air-soil gas-exchange of polybrominated diphenyl ethers (PBDEs) in Izmir, Turkey. *Environ Sci Technol* 2007;41:4986-92. DOI PubMed
106. Holoubek I, Dusek L, Sánka M, et al. Soil burdens of persistent organic pollutants--their levels, fate and risk. Part I. Variation of concentration ranges according to different soil uses and locations. *Environ Pollut* 2009;157:3207-17. DOI PubMed
107. Cui L, Wang S, Gao L, et al. Concentrations and trophic magnification of polychlorinated naphthalenes (PCNs) in marine fish from the Bohai coastal area, China. *Environ Pollut* 2018;234:876-84. DOI PubMed
108. Dat ND, Chang KS, Wu CP, et al. Measurement of PCNs in sediments collected from reservoir and river in northern Taiwan. *Ecotoxicol Environ Saf* 2019;174:384-9. DOI PubMed
109. Cui L, Ge J, Zhu Y, Yang Y, Wang J. Concentrations, bioaccumulation, and human health risk assessment of organochlorine pesticides and heavy metals in edible fish from Wuhan, China. *Environ Sci Pollut Res Int* 2015;22:15866-79. DOI PubMed
110. Ishaq R, Karlson K, Näf C. Tissue distribution of polychlorinated naphthalenes (PCNs) and non-ortho chlorinated biphenyls (non-ortho CBs) in harbour porpoises (Phocoena phocoena) from Swedish waters. *Chemosphere* 2000;41:1913-25. DOI PubMed
111. Parmanne R, Hallikainen A, Isosaari P, et al. The dependence of organohalogen compound concentrations on herring age and size in the Bothnian Sea, northern Baltic. *Mar Pollut Bull* 2006;52:149-61. DOI PubMed
112. Wang D, Atkinson S, Hoover-Miller A, Li QX. Polychlorinated naphthalenes and coplanar polychlorinated biphenyls in tissues of harbor seals (Phoca vitulina) from the northern Gulf of Alaska. *Chemosphere* 2007;67:2044-57. DOI PubMed
113. Falandysz J, Rappe C. Spatial Distribution in Plankton and bioaccumulation features of polychlorinated naphthalenes in a pelagic food chain in southern part of the Baltic Proper. *Environ Sci Technol* 1996;30:3362-70. DOI
114. Kim J, Shin ES, Choi SD, Zhu J, Chang YS. Polychlorinated naphthalenes (PCNs) in seafood: estimation of dietary intake in Korean population. *Sci Total Environ* 2018;624:40-7. DOI PubMed

115. Zhihua L, Gong Y, Holmes M, et al. Geospatial visualisation of food contaminant distributions: polychlorinated naphthalenes (PCNs), potentially toxic elements (PTEs) and aflatoxins. *Chemosphere* 2019;230:559-66. DOI PubMed
116. FERA - Food and Environment Research Agency Marine Scotland. Investigation into the levels of environmental contaminants in Scottish marine and freshwater fin fish and shellfish. Available from: www.nal.usda.gov/research-tools/food-safety-research-projects/investigation-levels-environmental-contaminants [Last accessed on 11 Apr 2022].
117. Niu S, Tao W, Chen R, et al. Using polychlorinated naphthalene concentrations in the soil from a southeast China e-waste recycling area in a novel screening-level multipathway human cancer risk assessment. *Environ Sci Technol* 2021;55:6773-82. DOI PubMed
118. Zhang L, Zhang L, Dong L, Huang Y, Li X. Concentrations and patterns of polychlorinated naphthalenes in surface sediment samples from Wuxi, Suzhou, and Nantong, in East China. *Chemosphere* 2015;138:668-74. DOI PubMed
119. Wang Y, Cheng Z, Li J, et al. Polychlorinated naphthalenes (PCNs) in the surface soils of the Pearl River Delta, South China: distribution, sources, and air-soil exchange. *Environ Pollut* 2012;170:1-7. DOI PubMed
120. Helm PA, Bidleman TF, Li HH, Fellin P. Seasonal and spatial variation of polychlorinated naphthalenes and non-/mono-ortho-substituted polychlorinated biphenyls in arctic air. *Environ Sci Technol* 2004;38:5514-21. DOI PubMed
121. Herbert BM, Halsall CJ, Villa S, et al. Polychlorinated naphthalenes in air and snow in the Norwegian Arctic: a local source or an Eastern Arctic phenomenon? *Sci Total Environ* 2005;342:145-60. DOI PubMed
122. Lee SC, Harner T, Pozo K, et al. Polychlorinated naphthalenes in the Global atmospheric passive sampling (GAPS) study. *Environ Sci Technol* 2007;41:2680-7. DOI PubMed
123. Vorkamp K, Falk K, Møller S, Bossi R, Rigét FF, Sørensen PB. Perfluoroalkyl substances (PFASs) and polychlorinated naphthalenes (PCNs) add to the chemical cocktail in peregrine falcon eggs. *Sci Total Environ* 2019;648:894-901. DOI PubMed
124. Braune BM, Muir DC. Declining trends of polychlorinated naphthalenes in seabird eggs from the Canadian arctic, 1975-2014. *Environ Sci Technol* 2017;51:3802-8. DOI PubMed
125. Verreault J, Houde M, Gabrielsen GW, et al. Perfluorinated alkyl substances in plasma, liver, brain, and eggs of glaucous gulls (Larus hyperboreus) from the Norwegian arctic. *Environ Sci Technol* 2005;39:7439-45. DOI PubMed
126. Kannan K, Hilscherova K, Imagawa T, et al. Polychlorinated naphthalenes, -biphenyls, -dibenzo-p-dioxins, and -dibenzofurans in double-crested cormorants and herring gulls from Michigan waters of the Great Lakes. *Environ Sci Technol* 2001;35:441-7. DOI PubMed
127. Yamamoto T, Noma Y, Hirai Y, Nose K, Sakai S. Congener-specific analysis of polychlorinated naphthalenes in the waste samples. Available from: https://www.osti.gov/etdeweb/biblio/20926838 [Last accessed on 11 Apr 2022].
128. Kohler M, Tremp J, Zennegg M, et al. Joint sealants: an overlooked diffuse source of polychlorinated biphenyls in buildings. *Environ Sci Technol* 2005;39:1967-73. DOI PubMed
129. Williams DT, Kennedy B, Lebel GL. Chlorinated naphthalenes in human adipose tissue from ontario municipalities. *Chemosphere* 1993;27:795-806. DOI
130. Kawano M, Ueda M, Falandysz J, Matsuda M, Wakimoto T. Polychlorinated naphthalenes (PCNs) in human adipose tissue in Japan. *Organohalogen compd* 2000;47:159-62. DOI
131. Witt K, Niessen KH. Toxaphenes and chlorinated naphthalenes in adipose tissue of children. *J Pediatr Gastroenterol Nutr* 2000;30:164-9. DOI PubMed
132. Kunisue T, Johnson-Restrepo B, Hilker DR, Aldous KM, Kannan K. Polychlorinated naphthalenes in human adipose tissue from New York, USA. *Environ Pollut* 2009;157:910-5. DOI PubMed
133. Schiavone A, Kannan K, Horii Y, Focardi S, Corsolini S. Polybrominated diphenyl ethers, polychlorinated naphthalenes and polycyclic musks in human fat from Italy: comparison to polychlorinated biphenyls and organochlorine pesticides. *Environ Pollut* 2010;158:599-606. DOI PubMed
134. Kilanowicz A, Skrzypinska-Gawrysiak M, Sapota A, Galoch A, Daragó A. Subacute toxicity of polychlorinated naphthalenes and their effect on cytochrome P-450. *Ecotoxicol Environ Saf* 2009;72:650-7. DOI PubMed
135. Klimczak M, Darago A, Bruchajzer E, et al. The effects of hexachloronaphthalene on selected parameters of heme biosynthesis and systemic toxicity in female wistar rats after 90-day oral exposure. *Environ Toxicol* 2018;33:695-705. DOI PubMed
136. Li C, Li J, Lyu B, et al. Burden and risk of polychlorinated naphthalenes in chinese human milk and a global comparison of human exposure. *Environ Sci Technol* 2021;55:6804-13. DOI PubMed
137. UNDP (United Nations, Department of Economic and Social Affairs, Population Division). World World population prospects: The 2015 revision. Key findings and advance tables (2015). Available from: http://esa.un.org/unpd/wpp/ [Last accessed on 11 Apr 2022].
138. Lundén A, Norén K. Polychlorinated naphthalenes and other organochlorine contaminants in Swedish human milk, 1972-1992. *Arch Environ Contam Toxicol* 1998;34:414-23. DOI PubMed
139. Akinrinade OE, Stubbings W, Abou-elwafa Abdallah M, et al. Status of brominated flame retardants, polychlorinated biphenyls, and polycyclic aromatic hydrocarbons in air and indoor dust in AFRICA: a review. *Emerging Contaminants* 2020;6:405-20. DOI
140. Gioia R, Eckhardt S, Breivik K, et al. Evidence for major emissions of PCBs in the west African region. *Environ Sci Technol* 2011;45:1349-55. DOI PubMed
141. Marek RF, Thorne PS, Herkert NJ, Awad AM, Hornbuckle KC. Airborne PCBs and OH-PCBs inside and outside urban and rural U.S. schools. *Environ Sci Technol* 2017;51:7853-60. DOI PubMed PMC
142. Wemken N, Drage DS, Abdallah MA, Harrad S, Coggins MA. Concentrations of brominated flame retardants in indoor air and dust from Ireland reveal elevated exposure to decabromodiphenyl ethane. *Environ Sci Technol* 2019;53:9826-36. DOI PubMed

143. Weber R, Herold C, Hollert H, et al. Life cycle of PCBs and contamination of the environment and of food products from animal origin. *Environ Sci Pollut Res Int* 2018;25:16325-43. DOI PubMed
144. A M, Cao R, Geng N, Zhu X, Chen J. Characteristics of PAHs, PCDD/Fs, PCBs and PCNs in atmospheric fine particulate matter in Dalian, China. *Chemosphere* 2022;288:132488. DOI PubMed
145. Li F, Jin J, Gao Y, et al. Occurrence, distribution and source apportionment of polychlorinated naphthalenes (PCNs) in sediments and soils from the Liaohe River Basin, China. *Environ Pollut* 2016;211:226-32. DOI PubMed
146. Pan X, Tang J, Chen Y, Li J, Zhang G. Polychlorinated naphthalenes (PCNs) in riverine and marine sediments of the Laizhou Bay area, North China. *Environ Pollut* 2011;159:3515-21. DOI PubMed
147. Castells P, Parera J, Santos FJ, Galceran MT. Occurrence of polychlorinated naphthalenes, polychlorinated biphenyls and short-chain chlorinated paraffins in marine sediments from Barcelona (Spain). *Chemosphere* 2008;70:1552-62. DOI PubMed
148. Pan J, Yang YL, Xu Q, Chen DZ, Xi DL. PCBs, PCNs and PBDEs in sediments and mussels from Qingdao coastal sea in the frame of current circulations and influence of sewage sludge. *Chemosphere* 2007;66:1971-82. DOI PubMed
149. Zennegg M, Schmid P, Kuchen A, et al. High PCB contamination detected in cattle from extensive farming in Switzerland. Available from: https://www.semanticscholar.org/paper/HIGH-PCB-CONTAMINATION-DETECTED-IN-CATTLE-FROM-IN-Zennegg-Kuchen/4f240b334f738bd162b44dd28c03370b316c9194 [Last accessed on 11 Apr 2022].
150. Mueller M. Personal communication. 2017. Forthcoming 2022
151. Domingo JL, Falcó G, Llobet JM, Casas C, Teixidó A, Müller L. Polychlorinated naphthalenes in foods: estimated dietary intake by the population of Catalonia, Spain. *Environ Sci Technol* 2003;37:2332-5. DOI PubMed
152. Isosaari P, Hallikainen A, Kiviranta H, et al. Polychlorinated dibenzo-p-dioxins, dibenzofurans, biphenyls, naphthalenes and polybrominated diphenyl ethers in the edible fish caught from the Baltic Sea and lakes in Finland. *Environ Pollut* 2006;141:213-25. DOI PubMed
153. Jiang Q, Hanari N, Miyake Y, et al. Health risk assessment for polychlorinated biphenyls, polychlorinated dibenzo-p-dioxins and dibenzofurans, and polychlorinated naphthalenes in seafood from Guangzhou and Zhoushan, China. *Environ Pollut* 2007;148:31-9. DOI PubMed
154. Martí-Cid R, Llobet JM, Castell V, Domingo JL. Human exposure to polychlorinated naphthalenes and polychlorinated diphenyl ethers from foods in Catalonia, Spain: temporal trend. *Environ Sci Technol* 2008;42:4195-201. DOI PubMed
155. Yang Y, Pan J, Zhu X, et al. Studies on coplanar-PCBs and PCNs in edible fish and duck in Qingdao and Chongming Island. Res Environ Sci 2009;22:194-8. DOI
156. Fernandes A, Mortimer D, Gem M, et al. Polychlorinated naphthalenes (PCNs): congener specific analysis, occurrence in food, and dietary exposure in the UK. *Environ Sci Technol* 2010;44:3533-8. DOI PubMed
157. Fernandes AR, Tlustos C, Rose M, Smith F, Carr M, Panton S. Polychlorinated naphthalenes (PCNs) in Irish foods: Occurrence and human dietary exposure. *Chemosphere* 2011;85:322-8. DOI PubMed
158. Rose M, Fernandes A, Mortimer D, Baskaran C. Contamination of fish in UK fresh water systems: risk assessment for human consumption. *Chemosphere* 2015;122:183-9. DOI PubMed
159. Fernandes A, Rose M, Smith F, Panton S. Geographical Investigation for Chemical Contaminants in Fish Collected From UK and Proximate Marine Waters. *Report FD* 2015;15. Available from: https://www.food.gov.uk/sites/default/files/media/document/fs102005reportfinal.pdf.
160. Wang Y, Zhang S, Fan M, et al. Polychlorinated naphthalenes in farmed Chinese mitten crabs in China: concentration, distribution and source analysis. *Environ Res* 2022;206:112582. DOI PubMed
161. Dong S, Li J, Zheng B, et al. Occurrence and source analysis of polychlorinated naphthalenes in raw cow milk. *Food Chem* 2022;381:132247. DOI PubMed
162. Li L, Sun S, Dong S, et al. Polychlorinated naphthalene concentrations and profiles in cheese and butter, and comparisons with polychlorinated dibenzo-. *p* ;95:203-16. DOI
163. Pan J, Yang Y, Zhu X, et al. Altitudinal distributions of PCDD/Fs, dioxin-like PCBs and PCNs in soil and yak samples from Wolong high mountain area, eastern Tibet-Qinghai Plateau, China. *Sci Total Environ* 2013;444:102-9. DOI PubMed