Journal of Technical Education Science No.59 (08/2020)
Ho Chi Minh City University of Technology and Education

REVIEW ON POLYCHLORINATED NAPHTHALENES (PCNs): PROPERTIES, SOURCES, CHARACTERISTICS OF EMISSION AND ATMOSPHERIC LEVEL

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Received 3/8/2020, Peer reviewed 14/8/2020, Accepted for publication 21/8/2020

ABSTRACT

Polychlorinated Naphthalenes (PCNs) have been included as new persistent organic pollutants (POPs) under Stockholm Convention in May, 2015. Thereafter, various studies working on the occurrence, toxicity and characteristics of PCNs in all environmental matrices and emission sources were conducted worldwide. However, these kinds of study have never been done in Vietnam, where has a high potential of PCNs pollution. Upcoming activities obeying the Stockholm Convention on limiting adverse effect of PCNs should be conducted as soon as possible by Vietnamese government. For the preparation, the relevant information on properties, sources of PCNs should be reviewed in advance. In this review paper, the characteristics of PCNs emitted from current sources and their atmospheric level measured worldwide were summarized. This review paper also offered diagnostic ratios those could be effectively used for distinguishing PCNs emitted/released or evaporated from technical mixtures and combustion-related sources. The information given in this review paper is useful for future studies in Vietnam.

Keywords: *polychlorinated naphthalenes; emission sources; diagnostic ratios; atmospheric level; Study in Vietnam.*

1. INTRODUCTION

Polychlorinated naphthalenes (PCNs) are a group of compounds that is composed of two fused benzene rings with one to eight chlorines substitution (molecular formula: $C_{10}H_{8-(m+n)}Cl_{(m+n)}$. General structure of PCNs is presented in Fig. 1, while numbering and substitution positions of 75 congers are shown in Table 1. PCNs have POPs-like characteristics such as persistence, biological accumulation, toxicity and long-range transport. PCNs are commonly compared to PCBs and they share a number of properties and industrial applications. In general, their levels of occurrence are lower than that of PCBs, ranging from 1 to 3 orders of magnitude [1, 2], but their dioxin-like toxicity is comparable to the most potent PCB congeners [3]. Therefore, the Stockholm convention recognizes PCNs as a persistent organic pollutant (POP) with a listing in Annex C which requires the minimization of unintentional release of PCNs with the goal of ultimate elimination. Due to persistent, accumulative and long-range transport properties, PCNs are detected with a wide range concentration in various environmental matrix and food webs such as ambient air, sediment, water, wastewater, fish and marine mammals, and human tissue not only in industrial areas but also in remote regions such as polar environment [4, 5, 6, 7].

Regarding to toxicity, a few PCN members investigated appear to exhibit high dioxin-like toxicity. PCNs potentially affect human and environmental health, as supported by occupational exposures, livestock poisonings, acute and chronic toxicity tests and the dioxin-like activity of PCNs [8, 9]. Some planar congeners are of similar biochemical toxicity to PCDD/PCDFs and coplanar PCBs [10, 11]. Through food webs, these compounds gradually accumulate and affect organisms of higher consumption, especially human being.

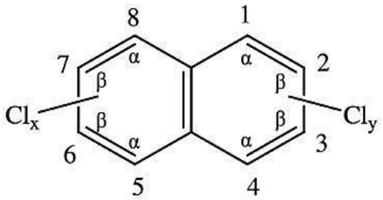

***Figure 1**. General structure of PCNs*

PCNs were started to produce in early 1900s and widely used in a variety of industrial applications such as dye-making, fungicides in the wood, textile and paper industries, plasticizers, oil additives, casting materials for alloys and lubricants for graphite electrodes [11, 12]. Although the production of PCNs was terminated at the end of 20th century due to the damage to human health and environment, these compounds are still released into environment by common sources such as historical use of PCNs, historical and present use of PCBs (PCNs are byproducts in production of PCBs), combustion and other thermal processes [4].

2. PROPERTIES OF PCNs

Physicochemical properties of PCNs vary with a wide range. Physical state of PCNs group change from low viscosity oils to high melting solids with intermediate wax like solids varying in crystallinity and melting points [2]. Some featured properties of PCNs are hydrophobicity, high thermal and chemical stability, and resistance to the weather of the environment, low flammability and low-medium volatility [11]. PCNs are practically insoluble in water, but are soluble in organic solvents. Table 2 shows the physicochemical properties of PCNs. Generally, PCNs are of high boiling points, low vapor pressures, low water solubility, low Henry's Law constant and large octanol/water partition coefficient (K_{ow}) and octanol/air partition coefficient (K_{oa}) values.

Several studies indicated that PCNs have the physical and chemical properties which are largely similar to those of PCBs [11, 13, 2], and Falandysz et al. [14] indicated that PCNs are dioxin-like compounds. PCNs have 4 feature characteristics like a POPs group as presented below:

Potential for long-range atmospheric transport

Atmospheric half-lives of PCNs with respect to gas-phase OH radical reaction were predicted by Puzyn et al. [15] as: 2 days (mono- CNs), 5 days (di-CNs), 10 days (tri-CNs), 19 days (tetra-CNs), 39 days (penta-CNs), 79 days (hexa-CNs), 163 days (hepta-CNs) and 343 days (octa-CN). The Stockholm Convention (Annex D) [16] recognizes an atmospheric half-life >2 days as a criterion for long-range transport potential. PCNs have been detected in clean and remote sites such as polar areas. As a group of POPs, PCNs can be rapidly dispersed through the atmosphere and tend to be redistributed on a global scale [17]. The winds carry the volatile POPs from warm regions to cold areas such as polar regions and high mountain areas where the POPs are trapped in snow, soils and vegetation through condensation. This process is called "cold-trapping effect" [18]. In spring, these trapped POPs are released into the eco-system again after the snow melts [19].

Bioaccumulation

The octanol/water partition coefficient (log K_{ow}) is an important bioaccumulation parameter that can be used as a surrogate measure to indicate the potential of an organic substance which is taken up in fatty tissues. This parameter can be used to predict and model the migration of hydrophobic organic compounds in soil and groundwater. Typically, log K_{ow} value greater than 5 is considered as high bioaccumulation under Stockholm Convention (2001).

High log K_{ow} values of PCNs indicate high potential of bioaccumulation and strong sorption of these compounds onto sewage sludge, soils and sediments. As indicated in Table 2, the log K_{ow} values of most PCNs (Tri-Octa CN: from 5.14 to 6.68 with a clear trend of increasing values with increasing chlorination) are generally greater than 5, indicating that they are lipophilic in nature and have the potential to biomagnify in food chains [4]. The presence of these compounds in biota and food chains provides the direct evidence for this characteristic.

Toxicity

PCNs have the potential to adversely affect human health and environment as supported by occupational exposures, livestock poisonings, acute and chronic toxicity tests, and the dioxin-like properties of PCNs. Some of the PCN members investigated appear to exhibit high dioxin-like toxicity [8, 9]. Additionally, all congeners of PCN are planar compounds, structurally similar to highly toxic 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD), and can contribute to an aryl hydrocarbon (Ah) receptor-mediated mechanism of toxicity, including a combination of toxic responses such as mortality, embryotoxicity, hepatotoxicity, immunotoxicity, dermal lesions, teratogenicity, and carcinogenicity [20]. Chloracne and liver damage have been recognized as the most common health effects observed after the exposure to PCNs and penta- and hexaCNs which seem to be the most toxic congeners in this respect [13].

A recent review of AhR mediated responses [14] of the most potent PCNs collates the relative potency factors associated with these congeners (Table 3). 20% of PCN congeners show relative potencies that vary between 0.003 and 0.000001, which is within the same range to that seen for some of the dioxin-like PCBs. The table which collates in vitro and in silico studies for the most potent PCNs, reported over the last 12 years, shows a general consensus over the greatest potency occurring among those congeners with 5 to 7 chlorines.

Persistence

According to Stockholm Convention (2001), if the half life of the chemical in water is greater than two months, or the half life in soil or sediment is greater than six months, it can be regarded as persistence in environment. The half-life data of individual PCNs are still limited. Some evidences show that PCNs have the long half-life values. In several studies with bacteria from soil, sewage sludge, or river sediment aerobic biodegradation was observed for mono- and di-CNs. Half-lives of 2-mono-CN in wood reserving sludge may vary from 38 to 104 days [21]. Jakobsson and Asplund [13] indicated that the half-life values of two hexa-CNs were remarkably long and comparable to those of several 2,3,7,8-chlorinated dibenzofurans.

3. CURRENT SOURCES OF PCNs

PCNs were widely applied in different fields. The most important applications of PCNs are in cable insulation, wood preservation, engine oil additives, electroplating masking compounds, feedstocks for dye production, dye carriers, capacitors and refracting index testing oils [12]. Large-scale manufacture of PCNs and their main uses were mainly from 1910 to 1980 under the trade names such as Clonacire Wax, Halowax, Nibren Wax, and Seekay Wax. Approximately 150,000 tons of PCNs have been produced over the world [11]. In US, the production of PCNs has decreased significantly since 1977. In 1980s, the critical decisions have been made to phase out the production and application of PCNs in the US and European countries because of their toxicity, bioaccumulation, long-range transport and environmental persistence [22]. In Japan, from 1940 to 1976, over 4000 tons of PCNs was produced. Since 1979, PCNs was banned for import and manufacture as well [23]. In the UK, the production was stopped in the mid-60s, although it was reported that in 1970 small amounts of PCNs were still being produced. It can be concluded that the production of PCNs was terminated at the end of the 20th century due to the recognition of their damage to the environment [24, 25]. Although the production of PCNs has been terminated, products containing PCNs in historical use are still a source of PCNs. Evaporation of PCNs from old or in-use products and the release from old capacitors and wires from electronic equipment in landfills can be potential sources of PCNs in the environment.

Table 1. *Congener number and position of chlorine atom for PCNs*

Congener	Position	Congener	Position	Congener	Position
MonoCN (2 congeners)		TetraCN (22 congeners)		CN54	1,2,3,6,7
CN1	1	CN27	1,2,3,4	CN55	1,2,3,6,8
CN2	2	CN28	1,2,3,5	CN56	1,2,3,7,8
DiCN (10 congeners)		CN29	1,2,3,6	CN57	1,2,4.5.6
CN3	1,2	CN30	1,2,3,7	CN58	1,2,4,5,7
CN4	1,3	CN31	1,2,3,8	CN59	1,2,4,5,8
CN5	1,4	CN32	1,2,4,5	CN60	1,2,4,6,7
CN6	1,5	CN33	1,2,4,6	CN61	1,2,4,4,8
CN7	1,6	CN34	1,2,4,7	CN62	1,2,4,7,8
CN8	1,7	CN35	1,2,4,8	HexaCN (10 congeners)	
CN9	1,8	CN36	1,2,5,6	CN63	1,2,3,4,5,6
CN10	2,3	CN37	1,2,5,7	CN64	1,2,3,4,5,7
CN11	2,6	CN38	1,2,5,8	CN65	1,2,3,4,5,8
CN12	2,7	CN39	1,2,6,7	CN66	1,2,3,4,6,7
TriCN (14 congeners)		CN40	1,2,6,8	CN67	1,2,3,5,6,7
CN13	1,2,3	CN41	1,2,7,8	CN68	1,2,3.5,6.8
CN14	1,2,4	CN42	1,3,5,7	CN69	1,2,3,5,7,8
CN15	1,2,5	CN43	1,3,5,8	CN70	1,2,3,6,7,8
CN16	1,2,6	CN44	1,3,6,7	CN71	1,2,4,5,6,8
CN17	1,2,7	CN45	1,3,6,8	CN72	1,2,4,5,7,8
CN18	1,2,8	CN46	1,4,5,8	HeptaCN (2 congeners)	
CN19	1,3,5	CN47	1,4,6,7	CN73	1,2,3,4,5,6,7
CN20	1,3,6	CN48	2,3,6,7	CN74	1,2,3,4,5,6,8
CN21	1,3,7	PentaCN (14 congeners)		OctaCN (1 congener)	
CN22	1,3,8	CN49	1,2,3,4,5	CN75	1,2,3,4,5,6,7,8
CN23	1,4,5	CN50	1,2,3,4,6		
CN24	1,4,6	CN51	1,2,3,5,6		
CN25	1,6,7	CN52	1,2,3,5,7		
CN26	2,3,6	CN53	1,2,3,5,8		

Table 2. *Physicochemical properties of PCNs*

Homologue	Melting Point (°C)	Boiling Point (°C)	Vapor pressure (Pa at 25°C)	Water solubility (µg/L)	Henry's Law constant (Pa m^3/mol)	Log K_{ow} (Ca.)	Log K_{oa} (Ca.)
Mono-CNs	-2.3-60	260	2.1	924 - 2870	36	3.93 - 3.97	5.93- 6.02
Di-CNs	37-138	285-298	0.17	137 - 474	-	4.20 - 4.63	6.55 - 7.02
Tri-CNs	68-133	Ca.274	0.13	17- 65	-	5.49 -5.50	7.19 - 7.94
Tetra-CNs	115-198	-	0.048	3.7 - 8.2	-	5.14 - 6.10	7.88 - 8.79
Penta-CNs	147-171	Ca.313	4.3×10^{-3}	-	11.9	5.67 - 6.49	8.79 - 9.40
Hexa-CN	194	Ca.331	9.5×10^{-4}	-	8.8	6.02 - 6.68	9.62 - 10.17
Hepta-CNs	194	Ca.348	3.7×10^{-4}	-	-	6.48 - 6.57	10.68 -10.81
Octa-CN	192	440	1.3×10^{-4}	0.08	4.8	6.43	11.64

Ca.: calculated or estimated

Table 3. *Ranges of combined in vitro and in silico relative effect potencies (REPs) for selected PCN congeners (adopted from Fernandes et al. [3]).*

Congener	In vitro REPs						In silico REPs	
	H4II-EROD	H411-EROD	H4II-luc		DR-CALUX - (pM)	Micro-EROD (pM)		
Ref	[55]	[8]	[10, 56]		[57]		[15]	
CN52	4.2×10^{-6}				$< 3.4 \times10^{-6}$	$< 1.8 \times10^{-6}$	$8..5 \times 10^{-6}$	3.8×10^{-5}
CN53					$< 1.8 \times10^{-6}$	$< 1.2 \times 10^{-6}$	$1..3 \times 10^{-8}$	5.2×10^{-6}
CN54	9.2×10^{-5}		$< 0. 69\times10^{-3}$	0.00017	0.00058		2.8×10^{-5}	5.5×10^{-5}
CN56	2.4×10^{-5}		0.00049				$2..3 x 10^{-5}$	5.6×10^{-5}
CN60	$< 4.2 \times 10^{-7}$			$<2.8\times10^{-5}$			$1..3 x 10^{-6}$	2.8×10^{-5}
CN63		0.002					$2..2 \times 10^{-5}$	2.2×10^{-5}
CN64		2×10^{-5}					1.1×10^{-4}	1.0×10^{-5}
CN66	0.00061		0.0024	0.0039	0.0012	0.00054	0.00069	0.0029
CN67	0.00028	0.002		0.001	0.00048		0.001	0.0017
CN68		0.002		0.00015	0.00049		0.00027	0.00011
CN69		0.002			1.1×10^{-4}	6.4×10^{-6}	8.3×10^{-7}	1.5×10^{-4}
CN70	0.0021		0.0095	0.00059	0.0028		0.0028	0.00071
CN71					$< 1.1 \times 10^{-6}$		4.3×10^{-5}	1.6×10^{-7}
CN72					6.0×10^{-5}	7.1×10^{-6}	1.0×10^{-4}	8.9×10^{-8}
CN73	0.0004	0.003	0.0006	0.001	0.00052		0.00038	0.0018
CN74					4.1×10^{-6}			1.0×10^{-7}
CN75					$1.0 x 10^{-5}$	$< 4.3 \times 10^{-6}$		

Table 4. *Emission factors and annual emission of PCNs in several industry processes in China as modified from Liu et al. [32]*

Sources	Emission factor in concentration (µg t^{-1})	Emission factor in TEQ (ng TEQ t^{-1})	Annual emission estimates (mg TEQ)
Iron ore sintering	14–1749	0.5–41.5	1390
Electric arc furnace	1970–4475	21.6–30.1	N/A
Cement kiln	242	3.7	N/A
Secondary copper smelting	141–9154	2.8–1989	860
Secondary aluminum smelting	575–13610	33.8–316	390
Secondary zinc smelting	3431	126	10
Secondary lead smelting	1336	20.1	9
Primary copper smelting	11.2–69.0	0.2–13.0	N/A
Primary magnesium smelting	3329	32.1	16.1
Cooking process	5.1–50.3	0.77–1.24	430–692
Thermal wire reclamation	2715–8650	90–100	N/A
Municipal solid waste incineration	71–53253	1.4–810	N/A
Medical waste incineration	981	17	N/A
Hazardous waste incineration	269–5763	5.4–27	N/A

NA: Not available.

PCNs are by-products of PCB production, Falandysz [11] indicated that PCB mixtures like the Arochlor or Clophen series may contain PCNs. He reported a median value of 0.0067% PCNs with a maximum of 0.087% and derives a potential release of 100 tones based on the worldwide production of PCBs. The concentrations of total PCNs in different PCB mixtures range from 1.8 to 870 µg g^{-1}. Yamashita et al. [26] also investigated the PCN concentration in 18 different commercial PCB mixtures and suggested that PCN concentrations ranged from 5.2 to 67 µg g^{-1} in Aroclors to ~731 µg g^{-1} in Sovol. With the PCN concentrations in the analyzed PCB mixtures, a global inadvertent by-production was estimated to be approximately 120-169 tons, which is <0.1% of the total global production of PCNs of 150,000 tons as estimated by Falandysz [11]. Nowadays, evaporation and release of PCNs from technical mixtures of PCBs are considered as an important source of PCNs.

Another important source of PCNs is unintentional emission of PCN from thermal processes. PCNs emitted from thermal processes were reported to be the most important sources with over 80% of estimated PCN emissions [4]. Several thermal processes were reported as the sources of PCNs, including municipal waste incineration (MWI) [23, 27, 28], nonferrous smelting processes [29], steel production, coking industries [30], and chloroalkali industries [31].

4. CHARACTERISTICS OF PCNs EMITTED FROM THERMAL PROCESSES

Liu et al. [32] summarized the emission factors of PCNs from 14 thermal processes in China (Table 4). It can be seen that PCN emissions from metallurgical processes are significantly higher than those from other processes. Among metallurgical processes, secondary aluminum smelting might be of the highest emission factor (EF) in term of mass concentration, however, secondary copper smelting is likely of the highest EF in term of TEQ. On the other hand, municipal solid waste incineration is one of the high EFs of PCNs among combustion processes.

Falandysz [11] indicated that PCN emission concentrations vary to a tremendous extent between different operational stages in waste incineration, and PCNs concentration of 15000, 4300, and 13000 ng/Nm^3 having been found in flue gas samples collected during startup, steady operation, and shutdown conditions, respectively [33]. With the exception of CN26 and CN29, all other PCN congeners have been reported in MSWI flue gas sample by Takasuga et al. [34]. Ba et al. [35] investigated the concentration of PCNs in 33 stack gas samples from 11 plants of secondary copper, aluminum, lead, and zinc recycling industries in China. Lower chlorinated PCNs are the dominant homologues, with mono- to tri-CNs making the most distributions to total mass concentration. Liu et al. [36] investigated the PCN emission from 122 stacks of several industrial processes in China and indicated four groups of homologue distribution as presented in Fig. 2. The results indicated that groups 1 and 2 with the dominances of di- and tri-CNs for 111 samples (91%), revealing that low chlorinated homologues mainly dominate in flue gas. However, nine samples with the dominance of tetra- and penta-CNs and two samples with the dominance of heptaCN were found. Hu et al. [28] also reported that mono-to tetra-CNs are the dominant congeners in stack gas of waste incinerators. PCNs emitted from the thermal destruction of wastes containing PCNs was observed by Noma et al. [23]. The results showed that PCNs in wastes were destroyed by thermal process and PCN congeners in stack gas were formed as by-product in combustion process. In some thermal processes, a strong correlation between PCNs formation and PCDFs formation has been confirmed by a number of studies [37], [38].

Similar formation pathways of PCNs and PCDFs from chlorophenols have been observed by Kim and Mulholland [39]. A good correlation between PCN and PCDF formation in thermal processes has been observed by numerous studies [27, 37, 38, 40]. Correlations between PCN and PCDF emissions from coking process and waste incinerators were reported by Liu et al. [30, 41]. A good correlation between PCN and PCDD/Fs concentrations in various fly ash samples collected from 20 thermal-related processes was also reported by Liu et al. [42].

Many studies have identified certain PCN congeners that are absent or occur at low levels in commercial PCN and PCB mixtures, but are enriched in combustion sources. Various workers have associated enrichment of the following CN congeners with combustion processes: 13, 18, 17/25, 24, 26, 27, 29 (or coeluting 28/29/43), 35, 39, 44, 36/45, 48, 50, 51, 52/60, 54, 62, 66/67, 70 and 73 [1, 23, 25, 34, 37, 43, 44, 45, 46, 49], and earlier studies summarized in Meijer et al. [24]. These congeners should be considered as markers of combustion processes.

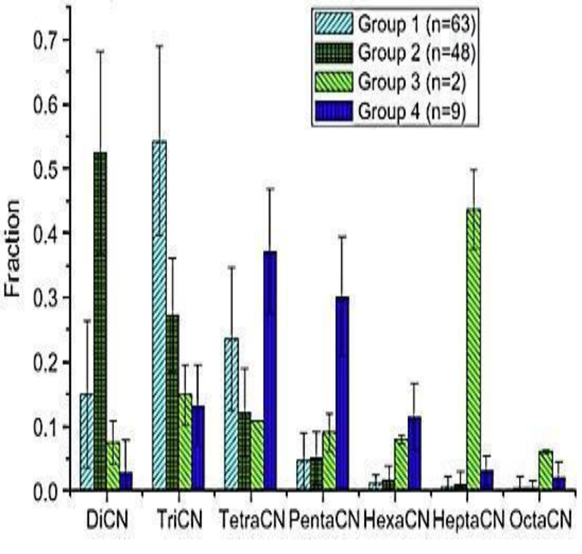

Figure 2. *Homologue distribution of PCNs emitted from 122 stacks of various industrial processes (Adapted from Liu et al. [36]).*

Based on the concentration of PCN congeners measured in different technical mixtures of PCNs reported by Noma et al. [49], Lee at al. [46] calculated the fraction of Σcombustion-related PCN congeners (including CN-20, 17/25, 26, 13, 18, 44, 36/45, 29, 27/30, 39, 35, 52/60, 50, 51, and 54 and -66/67) to ΣPCNs (tri- to octa-CNs) and found that the fraction Σcombustion-related PCNs/ΣPCNs for Halowax 1014 and other Halowaxes is less than 0.11. Furthermore, the above fraction for fly ashes discharged from various combustion processes (MWI, cement kiln, iron sintering, and medical waste incinerators) was estimated to be between 0.5 and 0.75 [1]. These results suggest that the fraction of Σcombustion-related PCNs/ΣPCNs could be used to distinguish combustion sources and historical use of PCNs. Liu et al. [32] compared some ratios of characteristic PCN congeners including CN45/36 to CN42, CN54 to CN53/55, CN66/67 to CN71/72, CN73 to CN74 between various thermal processes and technical PCNs, PCBs mixtures. The results indicate that these ratios varied only to a limited extent in the emissions from various thermal sources, but varied strongly between the industrial thermal sources and technical mixtures containing PCNs (including technical PCB mixtures). Generally, the ratios are significantly higher for thermal processes compared with those of technical mixtures containing PCNs. The ratios of CN45/36 to CN42, CN54 to CN53/55, CN66/67 to CN71/72 and CN73 to CN74 are lower than 1, 0.8, 2.5 and 0.4, respectively, corresponding to technical PCN mixture-related sources. The results can be useful for distinguishing PCNs emission from thermal processes and evaporative emission from historical use of technical mixtures containing PCNs. Lee et al. [46] employed the fraction of Σcombustion-related PCNs/ΣPCNs as an indicator to distinguish between evaporation sources (<0.11) and combustion emissions (>0.5). The combustion-related PCNs used in the formula included CN-17, CN-25/26/13, 27/30, 35, 36/45, 39, 50, 51, 52/60, 54, and 66/67.

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***Table 5.** Diagnostic ratios*

Disgnostic ratios	Thermal processes
CN45/36 to CN42	>1
CN54 to CN53/55	>0.8
CN66/67 to CN71/72	>2.5
CN73 to CN74	>0.4
Σcombustion PCNs/ΣPCNs	>0.5

5. PCNs IN AMBIENT AIR

PCNs are detected in ambient air with a wide range of concentrations. These compounds are detected in both industrial sites and remote sites. Higher concentration of these compounds was reported in the industrial sites in comparison to other sites [25, 50, 51]. In this literature review, on the concentration of these compounds in ambient air was focused as presented in Table 6.

Concentrations of PCNs in ambient air vary with a wide range and depend on where and when the sampling is conducted. A seasonal trend of ∑PCN was evident with higher levels observed during the colder months. PCNs apparently originated from combustion sources, which contribute to their high levels in winter (Helm et al., 2004). Typically, PCNs congeners with low chlorine atoms dominate in ambient air due to higher volatility. PCN homologues at Artic regions were dominated by tri-CNs which accounted for 60% of total PCNs, followed by contribution of tetra-CNs (Helm et al., 2004). Similar distribution was found at northern South China Sea [52] and Shanghai [53]. Die et al. [53] reported that the percentage of total PCN concentration in gas phase was 86-97.7% in summer and 85-98.7% in winter. Distribution of PCNs shifted towards the particle phase in winter, especially the higher homologues. Helm and Bidleman [54] indicated that percentage of CN homologues on solid phase range from <5% for tri-CNs and tetra-CNs, 20-30% for penta-CNs, 75% for hexa-CNs to >90% for hepta-CNs and octa-CNs. These figures indicate that PCNs congeners with high chlorine contents are dominant in particle phase. The reason for this distribution may come from their low vapor pressures.

6. CONCLUSION

It is clear that PCNs are toxic, persistent in environment and pose harmful effects on human health and ecosystem. They can be released from the use of products containing PCNs and emitted from any process utilizing high temperature. PCNs were included in the list of POPs and they have been receiving great attention by Stockholm Convention. To obey the Stockholm Convention, Vietnam should pay more attention to these toxic compounds and more studies on them should be conducted. This paper summarized the characteristics of PCNs emitted from current sources and their atmospheric level measured worldwide. This review paper also offered diagnostic ratios that could be effectively used for distinguishing PCNs emitted from technical mixture evaporation and combustion-related sources. The information given in this review paper is useful for future studies in Vietnam.

Table 6. *Comparison of PCN concentrations reported worldwide and this study*

Nation	**Concentration (pg m^{-3})**	**Note (dominant CNs)**	**Sampling time**	**Reference**
Indian	4.9 – 140	50 PCNs from tri-to octa-CN (tri- and tetra-CNs)	2006 (winter)	[58]
Pakistani	N.D. – 31		2011 (winter)	
Canada, USA	17 – 68	-	1995	[59]
China (South China Sea)	N.D. – 26.0	Tri-CNs	2005	[52]
Norwegian Arctic	9 – 48	Tri and tetra-CNs	2001-2003	[60]
Turkey				
Suburban and urban sites	5.20 – 162 (winter) 3.70 – 229 (summer)	32 PCNs from tri- to octa-CN (tri and tetra-CNs)	2004-2005	[5]
Industrial site	37.8±12.4 (winter) 55±6.0 (summer)			
East Asia (passive sampling for rural, urban and sub-urban sites)				
Japan	2 – 160	63 PCNs from tri- to octa-CN (TriCNs)	2008	[61]
China	23 – 110			
Taiwan	22.0			
South Korea	3.0 – 59			
Shanghai, China	8.2.0 – 102 (Summer) 16.5 – 61.1 (winter)	75 PCNs (TriCNs)	2013	[53]
Taoyuan, Taiwan		73 PCNs	2017	[47]
Urban and rural site	18.5 – 41.5	Tri- and Tetra-CNs	Winter	
	29.0 – 84.2		Summer	
Industrial site	82.4 – 387	Tetra- and Penta-CNs	Winter	
	94.8 – 153		Summer	

N.D.: None detected

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