



Polycyclic Aromatic Hydrocarbons in Soil and Human Health Risk Levels for Various Land-Use Areas in Ulsan, South Korea

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Multiplicity and complexity in sources account for polycyclic aromatic hydrocarbons (PAHs) in soil and health risk levels in industrial zones. In the present study, cancer risks (CR) for soil-bound carcinogenic PAHs were estimated and compared for the first time in seven different land-use areas adjacent to an industrial zone (Ulsan) in Korea. The entire study area has been recognized as a “low CR” zone ($10^{-6} < \text{value} < 10^{-4}$). Hence, all land-use areas were found to have significant ($>10^{-6}$) CR levels, except for an area used to store ore and iron scraps. Estimated CR levels were highest in the railroad area (RA) and traffic area (TA), followed by those in the industrial area (IA). In addition, exposure through dermal absorption (61–70%) and ingestion (21–39%) were the most common factors for CR levels in the study area. Among all health parameters, exposure duration, body weight, and open skin surface area were distinguished as most sensitive to total CR levels. Moreover, among all carcinogenic PAHs, indeno[1,2,3-c,d]pyrene and benzo[a]pyrene were most sensitive to CR levels. Creosote, which was utilized in railroad ties in RA and vehicular exhaust emission in TA, was classified as a source of soil-bound carcinogenic PAHs. Therefore, CR levels resulting from transportation activities were found to be two to three times higher than those obtained from industrial processes. Transportation activities in urban areas mostly serve to provide rapid and comfortable carriage for commuters. However, these facilities were mostly responsible for potential carcinogen exposure. This study directly challenges the conventional perception that industrial zones are the most polluted areas, especially when compared to transportation zones in urban areas. These findings can help local and national governments to better manage resources and maintain an economic balance.

Keywords: cancer risk, soil, PAHs, Monte Carlo, industrial city, South Korea

INTRODUCTION

Industries are the backbone of a country's economy. It is a common belief that industrial areas (IA) are more polluted than urban areas. Currently, the Korean Government is spending substantial funds to clean up industrial zones. Government policies on industrial disposal management, emission control techniques, and reuse and recycle systems have provided more sustainability within the industrial process system. However, Korean city managements are facing problems due to rapid urbanization, dense population, and waste volume. Although cities have several sources of pollution,

people are still migrating toward them. Moreover, cities are surrounded by high traffic density zones. Soils from dense traffic areas (TA) are enriched with more carcinogenic polycyclic aromatic hydrocarbons (PAHs), as compared to soils from other areas (Kim et al., 2019). Growing concentrations of soil-bound carcinogenic PAHs require attention from the scientific community in Korea.

Persistent organic pollutants such as PAHs are notable for their cancer-causing and mutagenic properties because of the fused aromatic rings in the structure (U.S. EPA, 2003). Due to hydrophobicity and stable chemical structure, the accumulation of PAHs onto the soil organic components is rapid (Abdel-Shafy and Mansour, 2016). The soil-bound PAHs are direct and indirectly exposed in the human body (Roy et al., 2017; Tarafdar et al., 2018; Ambade et al., 2021a; Ambade et al., 2021b; Ambade et al., 2021c; Ambade et al., 2021d). Vehicular exhaust emissions, fossil fuel combustions, excessive utilization of manufactured composts for horticulture, and industrial pyrolysis are the major sources of PAHs in soil environments (Bosetti et al., 2007; Arora and Reddy, 2013; Zhang et al., 2015; Ambade et al., 2020; Kumar et al., 2020; Ambade and Sethi, 2021). Moreover, long-term exposures to PAHs are responsible for development of cancerous tumors in human organs (IARC, 2010).

Monte Carlo simulations are a technique to analyze probabilistic uncertainty. The parameter values for exposure equations are randomly selected from distributions generated from the probability density functions for individual input parameters (Roy et al., 2019c; Roy et al., 2019d; Tarafdar et al., 2018). Hence, the role of these parameters in determining the total health risk can be established using sensitivity analysis (Roy et al., 2020). Exposure through ingestion, inhalation, and dermal absorption are the three routes by which PAHs in the soil enter the human body. Deposition and absorption of PAHs carrying particles on open surfaces of human skin, bio-accumulation of soil-bound PAHs in food, and soil particles erosion from the earth surface followed by inhalation are the common ways of human exposures. Apart from the PAHs levels in the soil, other age-specific risk assessment parameters such as body weight (BW), exposure durations (ED), exposure frequency (EF), skin surface area (SA), and inhalation rate are the most important factors for the risk value (Armstrong et al., 2004; Tarafdar et al., 2018; Tarafdar and Sinha, 2017a; Tarafdar and Sinha, 2017b; Roy et al., 2019a; Roy et al., 2019b; Roy et al., 2019c; Roy et al., 2019d). The role of those parameters in the total health risk levels can be determined through sensitivity analysis. Globally, Monte Carlo probabilistic approaches with sensitivity analysis are in common practice to estimate the human health risk levels (Roy et al., 2020; Tarafdar and Sinha, 2017a; Tarafdar and Sinha, 2017b).

Previous studies have focused on the monitoring and distribution of PAHs in agricultural soil, source identification of toxic PAHs, PAH levels in soils and sediments in coastal areas, and PAH levels in coastal fish. Recently, higher PAH levels in roadside soils at traffic-dense regions were observed in Ulsan (Jeon and Oh, 2019; Kim et al., 2019). At present, detailed investigations are required for source identification and health risk levels due to soil-bound carcinogenic PAHs over various

land-use area types. Overall, detailed investigations and comparisons of cancer risk (CR) levels are still required for soil-bound PAHs across various land-use areas near industrial zones. The current study aims to reduce research gaps through the following objectives: 1) compare CR levels in soil-bound PAHs for various land-use areas in industrial complex, 2) evaluate the impact of transportation [railroad area (RA) and TA] on CR levels, and 3) identify the most sensitive parameters and significant exposure routes for CR levels.

METHODOLOGY

Data Collection and Source Identification of PAHs

This study focused on CR assessment for soil-bound PAHs at various land-use areas near an industrial cluster in Korea. Previous published data (Jeon and Oh, 2019) on soil-bound PAHs were acquired to calculate CR levels: naphthalene (NaP), acenaphthylene (AcPy), acenaphthene (AcP), fluorene (Flu), phenanthrene (PhA), anthracene (AnT), fluoranthene (FluA), pyrene (Pyr), benzo[a]anthracene (BaA), chrysene (Chr), benzo[b]fluoranthene (BbF), benzo[k]fluoranthene (BkF), benzo[a]pyrene (BaP), indeno[1,2,3-c,d]pyrene (InP), dibenz[a,h]anthracene (DbA), and benzo[g,h,i]perylene (BghiP). The seven different land-use areas near Ulsan city and its IA were taken from the previous study. The land-use areas were as follows: waste treatment facilities area (WA), TA, child playground area (CA), IA, RA, ore and iron scraps area (OA), and residential area (ReA).

Interactions within the source delivering the PAHs directly influence the PAH profile. The diagnostic ratios used to trace PAH sources were generated from pyrolytic or petrogenic combustion, as shown in **Table 1**. PAHs such as AnT (AnT: 178) and fluoranthene (FluA: 202) are commonly used to distinguish between combustion and petroleum sources (Budzinski et al., 1997; Soclo et al., 2000). AnT/(AnT + FluA) ratios <0.1 and >0.1 are generally indicative of a petroleum and combustion source, respectively (Budzinski et al., 1997). For Fl/(Fl + Py) ratios, <0.5, 0.4–0.5, and >0.5 indicate petroleum/combustion, liquid fossil fuel combustion, and coal/wood/grass combustion sources, respectively (Budzinski et al., 1997). Moreover, the IP/[IP + B(ghi)P] ratios of <0.2, 0.2–0.5, and >0.5 represent the petroleum, liquid fossil fuel, and coal/wood/grass combustion sources, respectively. Finally, the BaA/(BaA + Chry) ratios of <0.2 and >0.2 indicate petroleum and pyrogenic/coal combustions, respectively (Budzinski et al., 1997).

Human CR Assessment

Human CRs were assessed from the exposure of the 16 carcinogenic PAHs in soil. The relative potency equivalency factor (PEF) to BaP was used to convert each PAH concentration level into BaP equivalent (BaP_{equ}) (U.S. EPA, 1993). Here, the following assumptions were used: 1) target age groups: 18 (teen) and 70 (adult); 2) exposure path: ingestion (ing), dermal absorption (derm), and inhalation (inh); 3) the BaP_{equ} value was considered for each PAH to calculate CR levels; and 4)

TABLE 1 | Calculated diagnostic ratio, ranges, and possible sources.

PAHs ratio	WA	TA	RA	CA	OA	IA	ReA	Ranges	Sources
IP/(IP + BghiP)	4.86E-01	4.98E-01	4.58E-01	4.21E-01	0.00E+00	6.11E-01	4.60E-01	<0.2 0.2–0.5 >0.5	Petrogenic product ^a Petroleum combustion (diesel) ^a Coal and softwood combustion ^a
BaA/(BaA + Chr)	5.11E-01	4.67E-01	4.05E-01	4.52E-01	3.94E-01	5.59E-01	4.87E-01	<0.2 >0.2	Petrogenic product petrogenic/coal ^b Combustion (gasoline) ^b
Ant/(Ant + Phe)	4.74E-01	3.85E-01	2.31E-01	4.44E-01	5.00E-01	4.19E-01	3.75E-01	<0.1 >0.1	Petrogenic product ^c Petrogenic product ^c
Fla/(Fla + Pyr)	5.03E-01	4.99E-01	4.62E-01	4.97E-01	—	5.10E-01	—	<0.5 >0.5	Petrogenic product ^d Coal/wood combustion ^d

^aYunker et al.(2002)

^bAkyüz and Cabuk(2010)

^cKong et al.(2011)

^dYu et al.(2014)

TABLE 2 | Cancer risk (CR) assessment parameters.

Input parameter	Description (unit)	Teen	Adults	Data distribution	References
Csoil	BaP equivalent concentration (mg/kg)	—	—	—	Present Study
ED	Exposure duration (year)	U (0, 18)	U (0, 52)	Uniform	Present Study
EF	Exposure frequency (day/year)	G (252, 1.01)	G (252, 1.01)	Log normal	U.S. EPA (2002)
BW	Body weight (kg)	A (35.9, 19.2)	A (62.8, 10.9)	Log normal	Chen and Lio (2006), U.S. EPA, 2002
AT	Averaging time (day)	25,550	25,550	Constant	—
CF	Conversion factor (kg/mg)	1.00E-06	1.00E-06	Constant	—
IR _{cd}	Soil ingestion rate (mg/day)	118	50	Constant	NIER (2016), U.S. EPA (2011)
HR	Air inhalation rate (m ³ /day)	A (12.1, 2.1)	A (14.3, 1.1)	Log normal	NIER (2016), MOE (2007)
PEF _{soil}	Soil particle emission factor (m ³ /kg)	1.32E+09	1.32E+09	Constant	U.S. EPA (1997)
SA	Surface area of skin that contacts soil (cm ² /day)	A (2,938, 1,171)	A (4,271, 440)	Log normal	NIER (2016), MOE (2007)
AF	Relative skin adherence factor (mg/cm ²)	0.1	0.08	Constant	U.S. EPA (2011), Cappelletti et al. (2018)
ABS	Dermal absorption factor	G (0.13, 1.26)	G (0.13, 1.26)	Log normal	Wester et al. (1990)
CSF _{ing}	Cancer slope factor for BaP (mg/kg/day)	G(7.3, 1.56)	G(7.3, 1.56)	Log normal	Chen et al. (2012)
CSF _{inh}	Cancer slope factor for BaP (mg/kg/day)	G(3.14, 1.8)	G(3.14, 1.8)	Log normal	Chen and Liao (2006)
CSF _{derm}	Cancer slope factor for BaP (mg/kg/day)	37.5	37.5	Constant	Hussain et al. (1998)

TABLE 3 | Equations to calculate exposures and CR levels.

Equation No	Equations	Parameter	References
1	$CDI_{ing} = \frac{CS_{soil} \times IR_{cd} \times CF \times ED \times EF}{BW \times AT}$	CDI _{ing} , chronic daily intake through ingestion; CDI _{inh} , chronic daily intake through inhalation; CDI _{derm} , chronic daily intake through dermal absorption;	U.S. EPA (1989), U.S. EPA (2004), U.S. EPA (2009)
2	$CDI_{inh} = \frac{CS_{soil} \times HR \times ED \times EF}{PEF_{soil} \times BW \times AT}$	CR _x , cancer risk (x = ing or inh or derm); CR (Total): sum of all CRs	
3	$CDI_{derm} = \frac{CS_{soil} \times CF \times SA \times AF \times ABS \times ED \times EF}{BW \times AT}$		
4	$CR_x = CDI_x \times CSF_x$		U.S. EPA (1989), U.S. EPA (1997)
5	$CR(Total) = CR_{inh} + CR_{ing} + CR_{derm}$		U.S. EPA (1989), Chiang et al. (2009)

risk assessment parameters such as air inhalation rate (HR), ED, BW, and soil ingestion rate (IR_{cd}) values were used based on Korean standard values (Table 2). Other model parameter values were taken from the standard values reported by the US Environmental Protection Agency (USEPA) (U.S. EPA, 2011). The chronic daily intake (CDI) of PAHs was calculated as CDI_{ing}, CDI_{inh}, and CDI_{derm}. The equations used to calculate CDI, CR

levels for individual exposure paths, and total cancer risk [CR(Total)] levels resulting from exposure to soils are shown in Table 3.

The Monte Carlo simulation tool from Oracle’s Crystal Ball (11.1.2.4.600) was used to calculate CR levels. Determining CR levels using Monte Carlo simulations for soil-bound PAHs is common in literature (Qu et al., 2015; Roy et al., 2020), as Monte

Carlo simulations help in analyzing probabilistic uncertainty. Risk value was calculated with 50,000 iterations along with a sensitivity analysis. Apart from the PAHs levels in the soil, other age-specific risk assessment parameters such as BW, ED, HR, EF, and SA were important considerations in determining risk (Table 2). Monte Carlo simulations and sensitivity analysis are universally used for CR analysis (e.g., Chen and Liao, 2006; Williams et al., 2013; Arora and Reddy, 2014, 2015; Gungormus et al., 2014; Tarafdar and Sinha, 2017a; Tarafdar and Sinha, 2017b; Roy et al., 2020). According to USEPA, CR value $>10^{-6}$ is considered as a significant level for CR (Wang et al., 2011; Li et al., 2014). The lifetime CR levels can be explained as very low, $CR \leq 10^{-6}$; low, $10^{-6} < CR < 10^{-4}$; moderate, $10^{-4} \leq CR < 10^{-3}$; high, $10^{-3} \leq CR < 10^{-1}$; and very high, $CR \geq 10^{-1}$ (NYSDOH, 2012).

Uncertainty and Variability Analysis

Variability and uncertainty are part of risk assessment processes, and they should be dealt with exclusively. Isolating these ideas in a reenactment drives us to distinguish the variety all the more precisely in the prediction because of limited knowledge and natural variations in the computation. Monte Carlo simulation from Crystal Ball 2D Simulation tool runs an outer loop to simulate the uncertainty values. To simulate the variability, the uncertainty values freeze while it runs an inner loop (of the whole model). This process repeats for hundred times to get the forecast distribution patterns. The 2D simulation output was compared with the previously done one-dimensional simulation results for both variability and uncertainty.

Moreover, deduction of CR induces uncertainties because of varieties in the health hazard evaluation parameters utilized in the estimations. Thus, for the parameters like ED, IR_d , BW, and HR, Korean standard values were used to reduce uncertainty. The sample assortment and investigation techniques additionally might have brought about uncertainty in CR assessment; specifically, the disappearance or addition of PAHs in the cooking activity was not taken into account.

RESULTS AND DISCUSSION

Concentration of Soil-Bound PAHs and Source Identification

The concentrations of soil-bound PAHs exhibited a wide range. The estimated soil-bound Σ 16 PAH concentrations were highest in RA (mean: 13,124 $\mu\text{g}/\text{kg}$), followed by those in IA (mean: 5,130 $\mu\text{g}/\text{kg}$), TA (mean: 3,728 $\mu\text{g}/\text{kg}$), and WA (mean: 3,724 $\mu\text{g}/\text{kg}$), as shown in Supplementary Figure S1A. Korean standards for soil-bound PAH levels are still unpublished. Other countries like Mexican (0–6 $\mu\text{g}/\text{g}$), Polish (0.02–0.05 $\mu\text{g}/\text{g}$), and Dutch (0.02–0.05 $\mu\text{g}/\text{g}$) standards have been compared for this study (Malawska 2000; Ray et al., 2008). As per Polish standards, OA and ReA were classified as low-pollution zones. Meanwhile, RA, IA, TA, and WA were classified as highly polluted sites.

The mean values of Σ 16 PAHs ranged from 368.5 to 13,152 $\mu\text{g}/\text{kg}$ throughout the study area. At RA, Pyr + BbF levels exhibited a maximum of 16% among all PAHs. BbF was

found to be highest in IA and WA, with a mean value of 766 and 472 $\mu\text{g}/\text{kg}$, respectively. In TA, concentration levels of InP were the highest (702 $\mu\text{g}/\text{kg}$) among all PAHs. Total PAHs as BaP toxic equivalent concentration ($\Sigma\text{BaP}_{\text{equ}}$) levels were estimated to exhibit a range of 44–1,930 $\mu\text{g TEQ}/\text{kg}$. The $\Sigma\text{BaP}_{\text{equ}}$ value was highest in RA (mean: 1,930 $\mu\text{g TEQ}/\text{kg}$), followed by that in TA (mean: 973 $\mu\text{g TEQ}/\text{kg}$), IA (mean: 781 $\mu\text{g TEQ}/\text{kg}$), and WA (mean: 633 $\mu\text{g TEQ}/\text{kg}$). Moreover, BaP_{equ} values were largest for BaP (mean: 857.5 $\mu\text{g TEQ}/\text{kg}$), followed by those in InP (583.5 $\mu\text{g TEQ}/\text{kg}$), as presented in Supplementary Figure S1B. The (BaP + InP) levels were responsible for 1.5 times higher $\Sigma\text{BaP}_{\text{equ}}$ values in TA, although IA exhibited higher Σ 16 PAHs levels than those in TA. Furthermore, BaP + InP (as BaP_{equ}) contributed 88%, 80%, 78%, and 75% to $\Sigma\text{BaP}_{\text{equ}}$ levels in TA, WA, IA, and RA, respectively. In the previous study higher PAHs levels were reported in Ulsan than those for other cities in Korea, Tokushima (Japan), Bangkok (Thailand), and Tarragona (Spain) (Jeon and Oh, 2019). Previous literature reported that numerous modern industrial units and substantial traffic near the Ulsan IA caused higher than normal ΣPAH (Lee and Dong, 2009; Yoo et al., 2010).

For sources, a diagnostic ratio analysis primarily identified the petrogenic products, petroleum combustion (diesel), coal/soft wood combustion, and petrogenic/coal combustion (gasoline) throughout the study area (Table 1). In RA, sources related to petrogenic products, petroleum combustion (diesel), and petrogenic/coal combustion (gasoline) IP/(IP + BghiP): 0.46; BaA/(BaA + Chr): 0.41; Ant/(Ant + Phe): 0.23; and Fla/(Fla + Pyr): 0.46 were the largest contributors to PAHs in soil. The elevated amount of ΣPAH in RA might be clarified using creosote as a wood additive for railroad ties. In previous research, high ΣPAH levels were also reported for RA (Baek, 2013). Railroad car movement and inadvertent fuel release are potential sources of PAHs in RA (Kim and Shin, 2001). Petroleum combustion (diesel), petrogenic/coal combustion (gasoline), and petrogenic products were also identified as major sources of soil-bound PAHs in TA. Pha, FluA, and BghiP, which are signature compounds in soils of dense TA, were found to be significant in TA (Kim et al., 2019). Except for RA, ΣPAH levels in WA and IA were two to three times higher compared to those in other areas; this was likely due to the wastes generated by petrochemical plants and their modern processing operations. In IA, IP/(IP + BghiP), BaA/(BaA + Chr), Ant/(Ant + Phe), and Fla/(Fla + Pyr) ratios were high (0.6, 0.6, 0.4, and 0.51, respectively). Sources related to industrial activities such as combustion [coal/soft wood combustion and petrogenic/coal combustion (gasoline)] and petrogenic products were mostly observed in IA.

In the Ulsan IA, petrochemical, automobile, shipbuilding, and oil refining are the primary industries that contribute to PAHs in soil. Combustion sources (coal, wood, petroleum) and petrogenic product sources were associated with soil pollution levels in WA. The petrogenic product and combustion sources were also commonly identified in CA, OA, and ReA. Moreover, traffic and industrial sources primarily contributed to soil pollution in ReA and CA. In particular, diesel, gasoline, and heavy oil combustion have been identified as major sources of soil-bound PAHs (Kwon and Choi, 2014). Ulsan is well known for

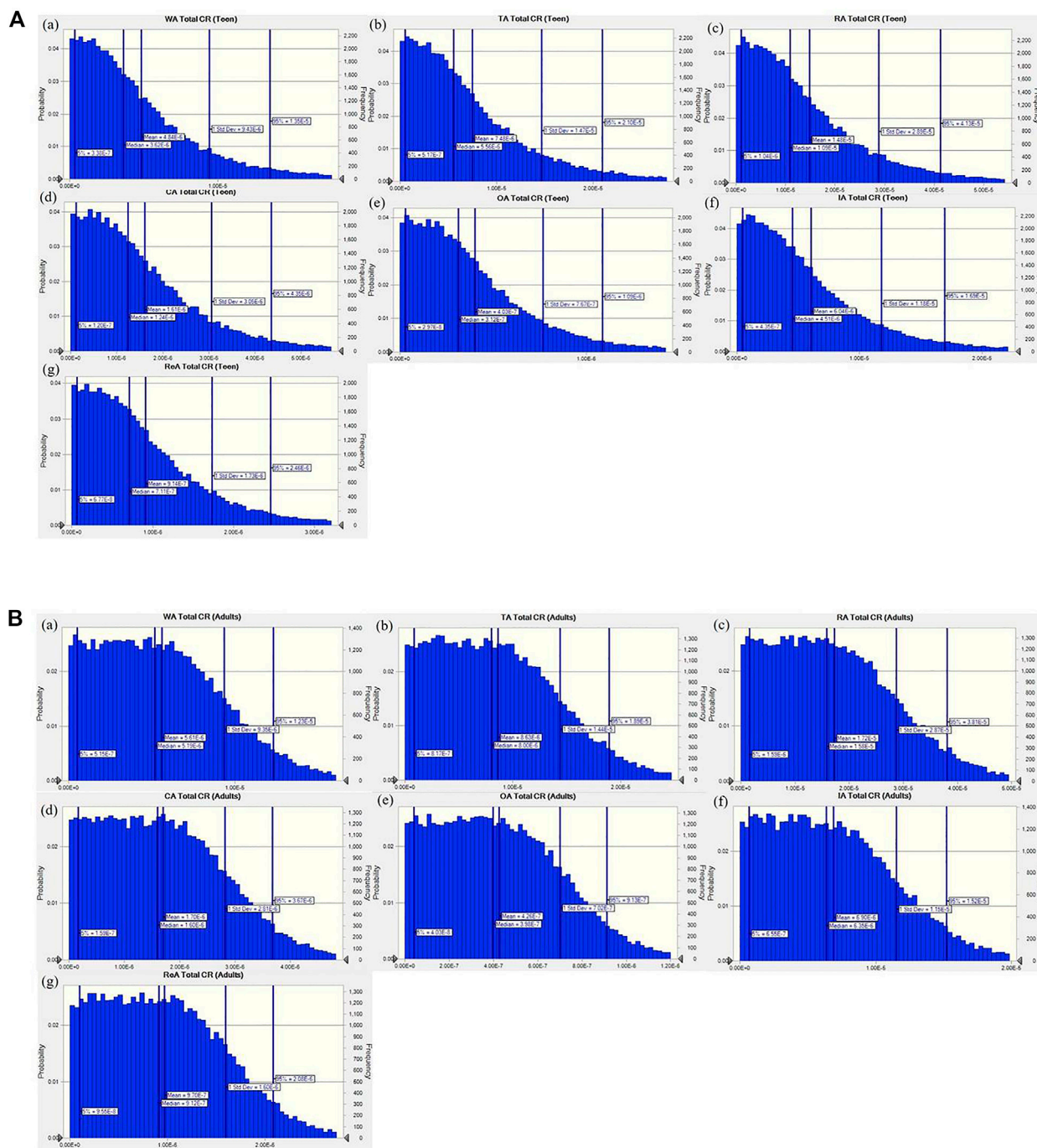


FIGURE 1 | (A) Probability density functions from Monte Carlo simulations used to predict CR (95% confidence level) from soil-bound PAHs for the teen group at (a) WA, (b) TA, (c) RA, (d) CA, (e) OA, (f) IA, and (g) ReA. **(B)** Probability density functions from Monte Carlo simulations used to predict CR (95% confidence level) from soil-bound PAHs for the adult group at (a) WA, (b) TA, (c) RA, (d) CA, (e) OA, (f) IA, and (g) ReA.

industrial clusters in Korea, containing refineries, non-ferrous metal smelting plants, petrochemical and automobile factories, shipbuilding complexes, and their vendors (Kwon and Choi, 2014).

The combustion of petrochemical products and direct emission of PAHs are possible sources of ΣPAH in the study

area (Kim and Shin, 2001; Chung et al., 2006). Two big refinery units are situated in Ulsan, and a lot of raw petroleum is imported to the Port of Ulsan. Therefore, storage, distribution (pipelines), and transportation (ground) processes are potential sources of ΣPAH (Jeon and Oh, 2019).

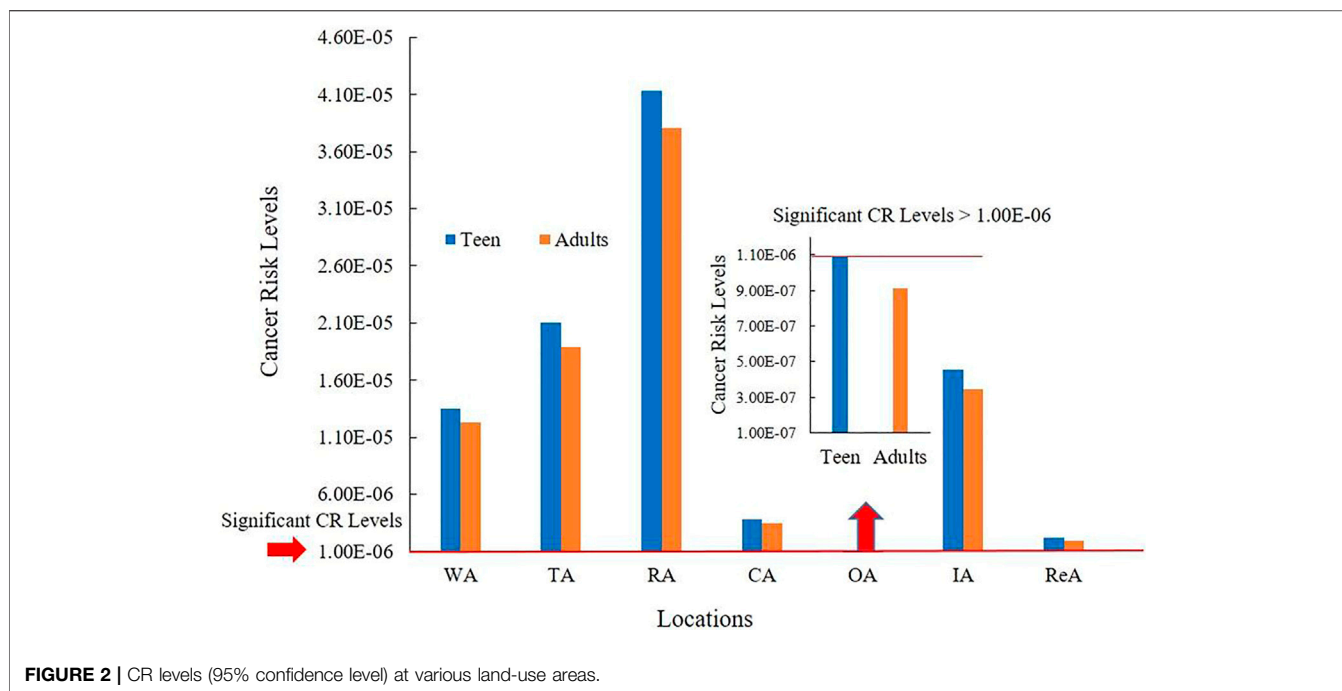


FIGURE 2 | CR levels (95% confidence level) at various land-use areas.

Human Health Risk Levels

The Σ PAH concentration (BaP_{eq}) was used as an input for the Monte Carlo simulations that calculated the 95% confidence levels for CR in the teen and adult age groups (Figure 1). Seven different land-use areas near the Ulsan industrial complex were considered for the CR assessment. Except for OA, CR(Total) for all other six areas was significant ($>10^{-6}$), and these areas were classified as low CR zones (Figure 2). The highest CR(Total) was found in RA (95% CL: $4.13E-05$ for teen; $3.81E-05$ for adult), followed by that in TA (95% CL: $2.10E-05$ for teen; $1.89E-05$ for adult), IA (95% CL: $1.69E-05$ for teen; $1.52E-05$ for adult), and WA (95% CL: $1.35E-05$ for teen; $1.23E-05$ for adult). ReA was identified as a significant CR zone but exhibited the second-lowest CR levels among the seven areas. Compared to ReA, CR levels were estimated to be 19, 10, 8, 6, and 2 times higher in RA, TA, IA, WA, and CA, respectively. OA was not only insignificant ($<10^{-6}$) but also exhibited a CR level two times lower than that of ReA.

Throughout the study area, CR levels through dermal exposure (adult: 79%; teen: 61%) and ingestion (teen: 39%; adult: 21%) were most significant (Supplementary Figure S2). Hence, CR through inhalation exposure was determined to be insignificant (10^{-10} – 10^{-11}). Kim et al. (2019) also reported insignificant CR levels through inhalation exposure in Korea. Additionally, the teen group exhibited a higher CR level than the adult group. High concentrations of soil-bound total PAHs and carcinogenic PAHs were responsible for the elevated CR levels in RA. Moreover, the presence of higher carcinogenic PAH (InP and BaP) levels was responsible for higher CR in RA. Likewise, higher InP and BaP levels were identified as the most probable PAHs that explained higher CR levels in TA than in IA. The diagnostic ratio analysis showed that the combustion of petroleum (diesel

and petrogenic (gasoline) were the major contributors other than petrogenic products. A significant correlation between traffic volume and CR levels was reported by Kim et al. (2019).

Overall, industrial activity can still be a major cause for elevated CR levels in IA. Oil refining, automobile manufacturing, petrochemical processes, shipbuilding, and smelting plants can all raise CR levels. Sustainable development with resource recovery and reuse are potential techniques to reduce pollution loads in IA. Moreover, fossil-fuel-free transportation systems can reduce PAH levels in TA. In Seoul, CR levels for soil-bound PAHs were reported in the range of $1.245E-06$ to $1.357E-05$ for children in playground dust (Tarafdar et al., 2020). This level is three and five times higher than the CA and ReA, respectively in Ulsan. Although Ulsan is a well-known industrial hub in Korea, RA and TA were identified as having the highest CR levels among the seven land-use areas. This outcome can change the conventional perceptions of Korea's residents and policymakers.

Sensitivity Analysis

A Monte Carlo analysis was conducted to identify the factors that are most sensitive to the CR levels (Figure 3). Sensitivity test results are shown in Table 4. The sensitivity to CR levels for all risk assessment parameters was evaluated. For the teen group, total CR levels were estimated to be most sensitive to the following parameters: ED (63%), BW (–26%), SA (6%), cancer slope factor for BaP (CSF_{ing} ; 3%), and dermal absorption factor (ABS; 2%). For the adult group, total CR levels were most sensitive to ED (87%), ABS (6%), BW (–5%), and SA (1%). BW was determined to be negatively sensitive to CR levels. ED (63–87%) was the most sensitive among all exposure routes (ingestion, dermal absorption, and inhalation) and age groups. The significant role of ED on CR

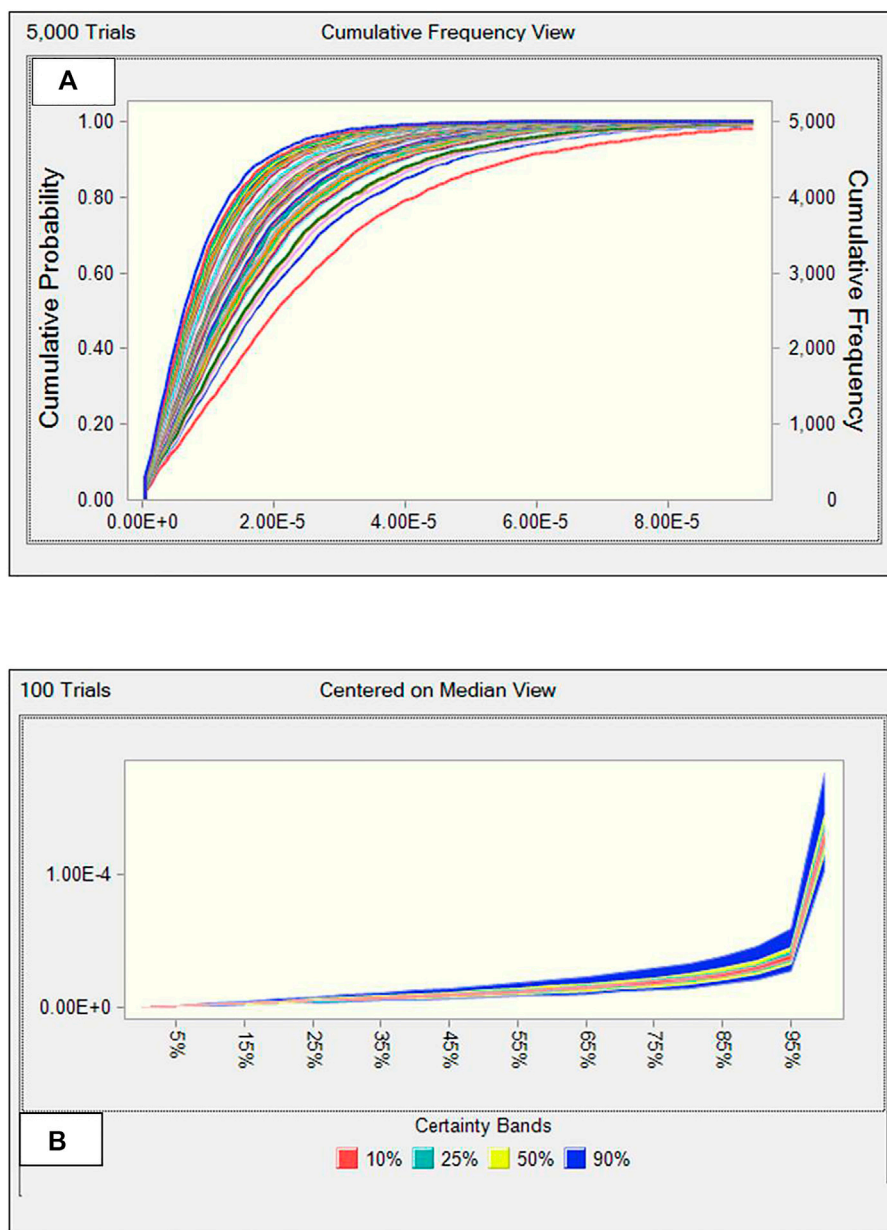


FIGURE 4 | Two-dimensional simulation plots of variability and uncertainty **(A)** overlay chart of risk curves for teen and adults and **(B)** trend chart of certainty bands for teen and adults at Ulsan.

levels has been previously reported (Chen and Liao, 2006; Chiang et al., 2009; Tarafdar and Sinha, 2017a). The negative BW value indicated the negative relationship between BW and total CR levels (Tarafdar and Sinha, 2017b; Chawada et al., 2020). For CR_{derm} and CR_{ing} levels, ED + BW was approximately 81% and 75% for the teen and adult groups, respectively. Risk assessment parameters, such as BW, ED, HR, ABS, CSF_{ing} , and SA, were identified as the most common factors sensitive to CR levels. In the present study, BW, ED, and HR were based on Korean standards, while the other parameters were taken from the U.S. EPA data. Determination of other risk assessment parameters value could be fruitful in future

research. Risk assessment efficiency might also be improved by using more specific health risk parameters.

Uncertainty and Variability Analysis

Two-dimensional simulation plots for variability and uncertainty are shown in **Figures 4A, B**. The overlay chart of risk curves and trend chart of certainty bands for teen in the case of CR from soil-bound PAHs have been reported in **Figures 4A, B**, respectively. The 2D simulation result shows that the risk curves are densely clustered near the center, although limited outlier curves are distributed to the Cumulative Frequency axis. The result shows

the lesser probability of having a much higher risk than the simulated. Moreover, for soil-bound PAHs at Ulsan area, the 95th percentile CR in two-dimensional study ($4.07E-05$ for teen) is similar to that of the 95th percentile CR of one-dimensional simulation ($4.13E-05$ for teen).

CONCLUSION

Ulsan is a well-known industrial city in Korea. In this study, CR levels were estimated for seven different land-use areas, based on soil-bound PAHs. Additionally, the most important exposure routes and sensitive parameters were identified. Although several industries and their associated endeavors (such as petrochemical and automobile factories, non-ferrous metal smelting plants, refineries, and shipbuilding complexes) contributed significant amounts of PAHs to the soil, concentration levels were approximately three times higher in RA than those in IA. CR levels in RA and TA were also higher than those in IA because of the larger amounts of carcinogenic PAHs in the soil. Moreover, exposure through dermal absorption and food ingestion were most significant for soil-bound PAHs. Risk assessment parameters such as ED, AF, and BW were identified as the most sensitive parameters for CR levels. While industrial activities are well-known anthropogenic sources for global pollution and negative human health impacts, carcinogenic PAHs resulting from transportation activities (RA and TA) caused elevated CR levels. Nowadays, cities are surrounded by traffic-intense areas with high vehicle density and railroads. There is a large possibility that the soil in these areas is being contaminated with carcinogenic PAHs, which could result in an unhealthy urban environment. Therefore, detailed investigations on CR levels, with respect to soil-bound PAHs

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in RA and TA, can be performed in future studies for cities in other areas and countries.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DR and JP conceived of the study design. DR, JK, WJ, and ML collected and interpreted the data. DR drafted the manuscript. DR and JP revised the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fenvs.2021.744387/full#supplementary-material>

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