



OPEN Exposure assessment and carcinogenic risk characterization of industrial chemical emissions in Incheon, South Korea

Yeowool Choi¹, Hyewon Kim², Tae-Yong Jeong³ & Sang Don Kim²✉

Rapid industrialization has intensified chemical emissions, raising urgent concerns about carcinogenic risks to surrounding communities. This study assessed the spatial distribution of industrial facilities emitting chemicals in Incheon Metropolitan City, South Korea, with a particular focus on Group 1 carcinogens. Using Geographic Information System (GIS) and multimedia exposure model (SimpleBox), we estimated exposure levels and cancer risks for residents within a 1-km radius of industrial facilities. The results demonstrated that approximately 22% of the region's population resides near chemical emission sources, with vulnerable facilities, including kindergartens, elementary schools, and medical institutions, located in these affected areas. Of particular concern, 9.4% of residents are potentially exposed to Group 1 carcinogens, including formaldehyde, benzene, chromium compounds, trichloroethylene, and cadmium compounds. Cancer risk assessments for chromium and cadmium compounds exceeded EPA management standards. This research underscores the urgent need for enhanced emission management policies at industrial facilities, the establishment of protective buffer zones, and strengthened collaboration between local communities and industries to mitigate these significant health risks.

Keywords Industrial chemical, Group 1 carcinogens, GIS analysis, Vulnerable group, Cancer risk assessment

The global usage of chemicals has increased dramatically, raising significant concerns regarding environmental and human health risks. Between 2000 and 2017, the quantity of chemicals utilized in the global chemical industry doubled from 1.2 billion to 2.3 billion tons. Chemical sales are expected to incline from 3.4 trillion euros in 2017 to 6.6 trillion euros in 2030, with Asia accounting for approximately 70%¹. The handling of chemicals can lead to increased environmental emissions, highlighting the need for continuous monitoring and management of chemical discharges. Chemical emissions from industrial facilities pose significant hazards to both human health and the environment. Exposure can lead to acute and chronic toxicity, skin irritation, mutagenicity, and reproductive toxicity. Previous studies have highlighted the health impacts on residents living near chemical emission sources. According to Brender, Maantay and Chakraborty² hazardous substances released from petroleum refineries negatively affect the health of nearby residents, contributing to cancer, leukemia, cardiovascular diseases, and respiratory disorders. Furthermore, residents living near industrial complexes are at higher risk of developing chronic respiratory diseases such as cough, sputum, and chronic bronchitis and skin irritations (e.g., eye- and nose-irritation) due to pollutants like SO₂, NO₂, CO, and particulate matter³.

Vulnerable groups, such as infants, children, and the elderly, are more susceptible to chemical exposure than adults, leading to a higher likelihood of health problems. Children, with their immature physiological systems and lower metabolic activity, have a reduced ability to eliminate external pollutants effectively. Additionally, they consume more air, water, and food per kilogram of body weight than adults, increasing their exposure to pollutants⁴. Elderly individuals are also at greater risk due to decreased physiological activity and weakened immune systems associated with aging, making them more susceptible to health issues when exposed to chemicals. Their overall health status is generally poorer than other age groups⁵.

¹Department of Economic and Environmental Research, The Incheon Institute, 98 Simgok-ro, Seo-gu, Incheon 22711, Republic of Korea. ²School of Environment and Energy Engineering, Gwangju Institute of Science and Technology, 123 Cheomdan-Gwagiro, Gwangju 61005, Republic of Korea. ³Department of Environmental Science, Hankuk University of Foreign Studies, 81 Oedae-Ro, Mohyeon-Eup, Cheoin-Gu, Yongin 17035, Gyeonggi-Do, Republic of Korea. ✉email: sdkim@gist.ac.kr

Incheon Metropolitan City, located in northwestern South Korea, is an industrial hub with extensive manufacturing, logistics, and industries centered around its airport and port. As of 2020, among the approximately 2,000 industrial facilities handling chemicals in Incheon, 69% are involved in manufacturing. The industrial structure is characterized by a high proportion of metal processing (11%), chemical and chemical product manufacturing (10%), and machinery and equipment manufacturing (9%), indicating emissions of a wide range of chemicals. However, research that comprehensively evaluating the status of chemical and carcinogen emissions from industrial facilities in Incheon and the resulting exposure risks to vulnerable groups remains insufficient.

Therefore, this study aims to analyze the spatial distribution of chemical emitting industrial facilities in Incheon and quantitatively assess the emission of Group 1 carcinogens and the exposure risk to vulnerable groups. Geographic Information System (GIS) analysis was used to spatially identify emission sources, nearby populations, and vulnerable facilities. A multimedia exposure model (SimpleBox) was employed to estimate human exposure levels and cancer risks for residents within a 1-km radius of industrial facilities.

Previous studies on chemical emissions have often focused on calculating nationwide total emissions or assessing the impact of a single pollutant⁶. However, these approaches do not fully capture the complex, localized risks faced by residents living near large industrial complexes where multiple carcinogens are emitted simultaneously. To address this gap, the present study is the first to conduct a population-based exposure assessment for multiple, specific Group 1 carcinogens in the Incheon. By comparing risk levels across different regions within the city, this research provides crucial data to derive targeted policy implications for reducing chemical emissions. The study results can enhance the effectiveness of chemical emission management, improve regulations for protecting residents in vulnerable areas, and provide fundamental data for establishing environmental health policies.

Methodology and data sources

Data collection

Study area and chemical data

The study area is Incheon Metropolitan City, located in northwestern South Korea. Incheon covers an area of 1,067.04 km² with a population of approximately 3 million, rendering it as the third most populous city in South Korea. In Incheon, the presence of major infrastructure such as an international airport and seaport has contributed to the development of diverse industrial sectors. Thus, industrial zones are interspersed with mixed-use residential and commercial areas, creating an urban environment with potential implications for chemical exposure patterns.

Annually, industrial facilities handling chemicals in South Korea are required under the Chemical Control Act to report the quantities of chemicals released into the environment (air, water, and soil) during their operations. In this study, the chemical emission data used pertains to substances used in the following processes: (i) chemicals produced at industrial facilities, (ii) raw materials and additives used in industrial facilities, (iii) auxiliary substances used in industrial facilities, (iv) chemicals stored in industrial facilities, (v) chemicals contained in waste processed at waste treatment facilities, and (vi) chemicals used for facility maintenance and repair.

Vulnerable group data

Population information by district in Incheon as of 2022 was obtained from the Korean Statistical Information Service and the National Spatial Information Portal. For integrated analysis between population distribution and other indicators, 100-m grid-based data were employed.

This study classified children and the elderly as populations vulnerable to chemicals and identified the distribution of facilities where these age groups are concentrated, such as kindergartens, elementary schools, and medical institutions. The study surveyed hospital level medical facilities including hospitals, dental hospitals, traditional Korean medicine hospitals, nursing hospitals, general hospitals, and tertiary hospitals, as well as midwifery centers with 30 or more beds to identify institutions with high potential for long-term chemical exposure.

Data analysis

Quantification of emissions

The South Korean Ministry of Environment annually surveys chemical emissions from industrial facilities that handle chemicals. The surveys cover chemicals that are used, produced, stored, or involve auxiliary substances in industrial operations. According to the Enforcement Decree of the Chemical Control Act, the chemicals subject to emission monitoring are classified as hazardous substances, air pollutants, volatile organic compounds, water pollutants, and chemicals designated by international organizations as carcinogenic, reproductive toxicants, or genotoxic substances.

For this study, chemical emission data for Incheon was obtained from the Ministry of Environment's Pollutant Release and Transfer Register, focusing on industrial facilities with annual emissions of 1 kg or more between 2016 and 2022. Carcinogenic substances were classified based on categories established by the International Agency for Research on Cancer (IARC) under the World Health Organization (WHO).

GIS analysis

GIS analysis was performed using Incheon's administrative boundary data to examine the spatial distribution of chemical emissions from industrial facilities and assess exposure risk to surrounding populations and vulnerable institutions. Location information (coordinates) of chemical emitting industrial facilities in Incheon were obtained from the Ministry of Environment's Pollutant Release and Transfer Register. For spatial data analysis,

QGIS 3.32 program was used to set 1 km buffer zones around each chemical emission source and identify the population and vulnerable facilities within these areas.

Atmospheric concentration modeling using simplebox 4.0

This study evaluated human exposure levels and cancer risks associated with five Group 1 carcinogens emitted from industrial facilities in Incheon: formaldehyde, benzene, chromium and its compounds (hereafter, chromium), trichloroethylene, cadmium, and its compounds (hereafter, cadmium).

To estimate the atmospheric concentrations of these chemicals, the SimpleBox 4.0 model was utilized. SimpleBox 4.0 is a multimedia mass balance model that evaluates the fate of chemical substances by simulating various mass flow processes to and from the environmental compartments.

The model was run using a combination of the model's default values and user-defined inputs to reflect the conditions of the Incheon region. The primary inputs for the model were the annual air emission rates for each of the five carcinogens as of 2022. To calculate the Predicted Environmental Concentration in air (PEC_{air}) for vulnerable areas within a 1-km radius of carcinogen emitting facilities, the model's area of influence was set to 100 km². In addition to this spatial setting, other meteorological parameters were specifically defined: average temperature of 12 °C, wind-speed of 3 m/s, and average precipitation of 1000 mm/year. Furthermore, specific physicochemical properties for each carcinogen, such as molecular weight, melting point, K_{ow} , vapor pressure, and water solubility, were manually input based on substance-specific data.

The modeling was performed using the default scenario case settings provided within the SimpleBox 4.0 software. Various fractional distribution coefficients were based on the model's default parameters⁷. The primary output from the model was the Predicted Environmental Concentration in air (PEC_{air} , µg/m³), which was subsequently used for risk assessment. The complete list of input parameters and the primary governing equations used in the model are detailed in the Supplementary Information.

Inhalation exposure and cancer risk assessment

The average daily dose (ADD, mg/kg-day) by inhalation for the population residing near emission facilities was calculated as Eq. (1)⁸.

$$ADD = \frac{PEC_{air} \times IR \times EF \times ED}{BW \times AT} \quad (1)$$

- PEC_{air} (µg/m³): predicted atmospheric concentration at industrial facility scale.
- IR (inhalation rate, m³/day): 20 m³/day, a standard default value for an adult's average daily air intake used for deriving Human Equivalent Concentrations (HECs) in the US EPA⁹.
- EF (exposure frequency, day/year): 350 days/year, a standard assumption for residential exposure provided in the EPA's supplemental guidance on default exposure factors¹⁰.
- ED (exposure duration, year): 30 years, representing a long-term residential exposure period, which is a standard default value in EPA risk assessment guidance¹⁰.
- BW (body weight, kg): 70 kg, a standard reference value for an adult male, used as a default in EPA guidance¹⁰.
- AT (average exposure time, year): 70 years, representing a typical lifetime for carcinogenic risk assessment, as recommended in EPA guidance¹⁰.

Cancer risk (CR) was calculated using PEC_{air} and the inhalation unit risk provided by the US Environmental Protection Agency^{10,11} (Eqs. 2, 3). The calculated cancer risk values were utilized to quantitatively evaluate the potential health hazards in vulnerable areas surrounding industrial facilities emitting carcinogens. $CR < 10^{-6}$ represents low risk level, indicating less than one cancer case per million people, $10^{-6} \leq CR < 10^{-4}$ is moderate risk level, potentially requiring regulatory review. $CR \geq 10^{-4}$ is high risk level, requiring immediate regulatory and reduction measures¹².

This study incorporates the chemical-specific Inhalation Unit Risk (IUR), which represents the upper-bound excess lifetime cancer risk per unit of concentration¹³. The IUR values for each of the five carcinogens were obtained from the U.S. EPA's Integrated Risk Information System (IRIS) database¹⁴. For substance groups such as chromium and cadmium, the IUR values were based on assessments of their most toxic inhalable forms, hexavalent chromium compounds¹⁵ and cadmium fumes (e.g., cadmium oxide)¹⁶ and were conservatively applied to the entire group, as specific IURs for all individual compounds are not available. The specific IUR value used for each substance is provided in the Supplementary Information (Table S1).

$$CR = EC \times IUR \quad (2)$$

$$EC = \frac{PEC_{air} \times EF \times ED}{AT} \quad (3)$$

- EC: lifetime average exposure concentration (µg/m³).
- IUR: inhalation unit risk (µg/m³)⁻¹.
- EF (exposure frequency, day/year): 350 days/year¹⁰.
- ED (exposure duration, year): 30 years¹⁰.
- AT (average exposure time, year): 70 years¹⁰.

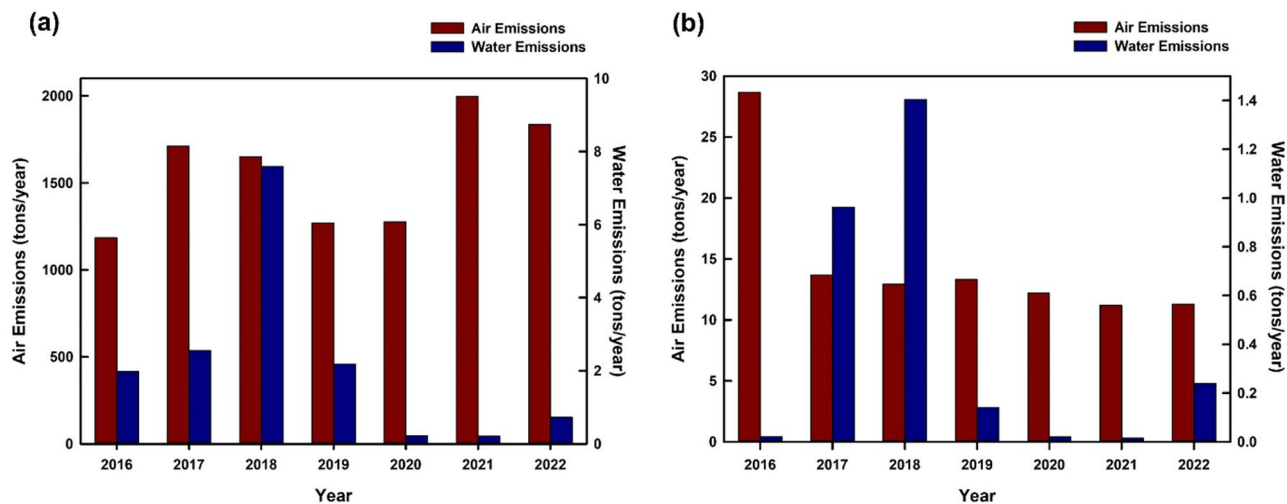


Fig. 1. Annual chemical emissions (a) and group 1 carcinogen emissions (b) from industrial facilities in Incheon. The left axis (red) represents air emissions, and the right axis (blue) represents water emissions.

Chemical name	Number of emission facilities	Air emissions (kg/year)
Ethyl acetate	15	361,952
Toluene	19	304,447
Methyl alcohol	19	282,368
Dichloromethane	8	196,649
Methyl ethyl ketone	10	190,890

Table 1. Number of emission facilities and air emissions for the top five chemicals by emission volume from industrial facilities in Incheon. No water emissions were detected for these chemicals; therefore, air emissions are equivalent to total emissions.

Results and discussion

Characteristics of chemical emissions

Chemical emissions

As of 2022, emission surveys covered 20 chemicals handled at quantities of 1 ton/year or more and 395 chemicals handled at 10 tons/year or more. This study estimated annual chemical emissions in Incheon by summing the chemical emissions from each industrial facility based on the Chemical Release and Transfer Register. Unintentional chemical releases from accidents were excluded, as the focus was solely on direct emissions from industrial processes. Soil emissions were also excluded due to either their absence or levels below 1 kg.

Between 2016 and 2022, the average annual air emissions from industrial facilities in Incheon were 1,561 tons/year (range: 1,184–1,996 tons/year), while average water emissions were 2.2 tons/year (range: 0.2–7.6 tons/year). Water emissions peaked in 2018 (7.6 tons/year) before showing a declining trend (Fig. 1a). Overall, emissions generally decreased after 2018, a trend that might be attributed to the implementation of the “Incheon Metropolitan City Ordinance on Chemical Management” in 2017 and the “Designation Notice of Toxic Substances” in 2018. These regulatory measures likely contributed to emission reductions.

Conversely, air emissions initially declined until 2020, followed by a sharp increase in 2021. This pattern could be attributed to the contraction of industrial activities due to coronavirus disease 2019 (COVID-19) in 2020 and the partial normalization of production activities in 2021. Among the top five emitting facilities in 2021, two began reporting emissions that year. Notably, the facility with the highest chemical emissions in 2021 reported a 14-fold increase compared to 2020, indicating the pandemic’s influence on emission patterns.

As of 2022, 153 industrial facilities in Incheon were reported to emit chemicals. The top five chemicals by emission volume were ethyl acetate, toluene, methyl alcohol, dichloromethane, and methyl ethyl ketone (Table 1). Of the total chemical emissions, ethyl acetate accounted for 20%, toluene 17%, methyl alcohol 15%, methyl ethyl ketone 11%, and dichloromethane 10%. The fact that these top five chemicals constituted 73% of total emissions while not being emitted from many facilities indicated that large-scale industrial facilities handled these chemicals in substantial quantities. Short-term, high-concentration exposure to ethyl acetate can cause eye, nose, and throat irritation, headaches, and vomiting, while long-term exposure may lead to respiratory and cardiovascular issues¹⁷.

The top five chemicals emitted from industrial facilities in Incheon were sodium hydroxide, sulfuric acid, hydrogen chloride, nickel and its compounds, and copper and its compounds (Table 2). Industrial facilities emitting sodium hydroxide accounted for approximately 48% of all chemical-emitting industrial sites in the

Chemical name	Number of emission facilities	Air emissions (kg/year)	Water emissions (kg/year)
Sodium hydroxide	74	1,428	0
Sulfuric acid	65	1,570	0
Hydrogen chloride	51	95,499	0
Nickel and its compounds	42	1,481	34
Copper and its compounds	41	523	156

Table 2. The top five chemical substances with the highest number of emitting facilities in Incheon industrial sites.

Chemical name	Emission facilities			Vulnerable groups			
	Number of facilities	Air emissions (kg/year)	Water emissions (kg/year)	Population	Number of kindergartens	Number of elementary schools	Number of hospitals
Formaldehyde	24	7,294	228	162,973	17	8	8
Benzene	3	2,776	-	30,268	6	3	1
Chromium and its compounds	31	823	11	156,002	14	7	8
Trichloroethylene	2	366	-	9,471	-	1	-
Cadmium and its compounds	2	39	-	24,515	3	2	3

Table 3. Status of group 1 carcinogen emission facilities in Incheon and vulnerable groups within a 1-km radius. The emission facilities section presents the number of facilities emitting each of the five group 1 carcinogens, along with their air and water emissions. The vulnerable groups section includes the population, number of kindergartens, elementary schools, and hospitals within a 1-km radius of industrial facilities emitting group 1 carcinogens.

region. Both nickel and copper compounds were confirmed to be released into the air and water environments. Sodium hydroxide, which was emitted by the largest number of industrial facilities, was identified as particularly hazardous and could cause severe skin corrosion, chemical burns, and eye damage upon contact¹⁸.

Carcinogen emissions

The IARC, under the WHO, aims to identify and evaluate chemicals that may cause cancer in humans and has designated carcinogens into four categories according to a standardized approach. Group 1 includes 133 substances that are confirmed to be carcinogenic to humans. Group 2 A includes 96 substances that are probably carcinogenic to humans according to animal research results. Group 2B comprises 322 substances that have insufficient animal research results but are possibly carcinogenic to humans. Group 3 includes 501 chemicals for which there is insufficient research on carcinogenicity to draw conclusions regarding human carcinogenicity¹⁹.

From 2016 to 2022, the average annual emission of IARC groups 1, 2 A, and 2B carcinogens from industrial facilities in Incheon was 143 tons/year (range: 61–307 tons/year), mostly identified as air emissions. Carcinogen emissions revealed a gradual decrease after 2018, followed by a sharp increase in 2021 (Figure S1). The average annual emission of Group 1 carcinogens from 2016 to 2022 was 15.2 tons (range: 11.2–28.7 tons), with an average air emission of 14.8 tons and an average water emission of 0.4 tons (Fig. 1b). The air emissions of Group 1 carcinogens decreased sharply after 2017 and then showed a steady decreasing trend, which might be attributed to the complete revision of the “Incheon Metropolitan City Ordinance on Chemical Management” in 2017, indicating that chemical emissions were influenced by the related regulations.

Group 1 carcinogen emissions

The Group 1 substances emitted from industrial facilities in Incheon were shown in (Table 3): volatile organic compounds including formaldehyde, benzene, and trichloroethylene, and heavy metals including chromium and cadmium. In Incheon, 42 industrial facilities were identified as sources of Group 1 carcinogen emissions, with chromium and formaldehyde being the most commonly emitted substances. The emission quantities were 7.5 tons of formaldehyde, 2.8 tons of benzene, 0.8 tons of chromium, 0.4 tons of trichloroethylene, and 0.04 tons of cadmium. Among these, formaldehyde and chromium had water emissions of 0.2 tons and 0.01 tons, respectively.

Formaldehyde is widely employed as an adhesive in plywood and compressed wood products, including a disinfectant and preservative. Benzene is used as a raw material for plastics, synthetic fibers, and synthetic rubber in the petrochemical industry, as well as an industrial solvent. Trichloroethylene is used as a cleaning agent for metal equipment and as a refrigerant, playing an important role as a solvent in surface treatment processes. Chromium is employed to plating of automotive parts and electronic devices and is used as an anti-corrosion agent to improve the corrosion resistance of steel products. Furthermore, cadmium is used as a raw material for nickel-cadmium batteries, including for metal coating and pigment manufacturing.

Formaldehyde, a Group 1 carcinogen, poses significant health risks to humans. Exposure via inhalation and dermal routes is linked to malignancies, including myeloid leukemia and nasopharyngeal carcinoma, as well

as acute effects such as mucosal irritation and dermatitis²⁰. Among Group 1 carcinogens, benzene was emitted at 3.7 tons annually from industrial facilities in Incheon, and exposure to this chemical could lead to leukemia and blood disorders. In a study by Yin, et al.²¹ a cohort study was conducted on benzene handling workers (approximately 75,000) and a control group of workers (approximately 35,000) in 216 factories in 12 cities in China. The incidence of acute myeloid leukemia in the benzene exposed group was three-fold higher than in the non-exposed group, indicating that benzene is correlated with blood diseases.

Vulnerable group analysis results

When analyzing vulnerable regions and facilities from environmental hazards, proximity is typically determined by measuring a distance of 0.5–1 miles from the environmental hazard²². According to Currie, et al.²³ within a 1-mile radius of 1,600 chemical emission facilities in the United States, the concentration of air pollutants, especially benzene, formaldehyde, chromium, lead, increased; however, no significant differences were observed beyond 1 mile. The proportion of low-birth-weight babies born within 1 mile of industrial facilities increased by approximately 3%, and children of women living within 1 km of chemical exposure points had higher neural tube defects, lymphoma, and cellular tumors. Furthermore, the risk of leukemia was found to increase in residents living within 0.5 miles of chemical exposure points^{23,24}. Therefore, in this study, vulnerable groups were identified based on a 1-kilometer radius surrounding industrial facilities that emit chemicals. These groups included both the residents living within this radius and nearby vulnerable facilities: kindergartens, elementary schools, and medical institutions.

Chemical vulnerable groups

As of 2022, the total population residing in Incheon was 3,048,141, with 384 kindergartens, 270 elementary schools, and 218 medical institutions. For research purposes, the locations of 153 industrial facilities with chemical emissions of 1 kg or more out of 208 chemical handling industrial facilities in Incheon were identified using GIS. Thus, the population residing within a 1-km radius of chemical emitting industrial facilities was calculated to be 657,797, indicating that approximately 22% of Incheon citizens resided within a 1-km radius of chemical emission facilities (Fig. 2a). Vulnerable facilities located within a 1-km radius of chemical emission facilities included 76 kindergartens, 46 elementary schools, and 35 medical institutions, representing 20% of kindergartens, 17% of elementary schools, and 16% of medical institutions out of the total number of vulnerable facilities in Incheon (Fig. 2b).

According to previous studies, children living within 5 km of industrial complexes with concentrated wood, electronic products, textile, plastic, paper containers, adhesives, and resin manufacturing had considerably higher risks of respiratory disease^{25,26}. The incidence of cough and sputum in the experimental group of children was 16.2% and 21.2%, respectively, which is approximately 3.89- and 6.71-fold higher than the control group²⁵. Furthermore, the probability of sputum symptoms increased 5.15-fold compared to the control group as the duration of residence increased. The average daily inhalation of particulate matter in children living near industrial areas was more than 3-fold higher than the control group, and their lung function was considerably reduced compared to the control group²⁶. Given that early signs of obstructive pulmonary disease were noted in some children, air pollutants emitted from industrial complexes appear to be closely related to the lung development and respiratory health of growing children over the long term.

Group 1 carcinogen vulnerable groups

Characteristics of vulnerable groups As of 2022, the total emission of carcinogens (Groups 1, 2 A, 2B) in Incheon was approximately 282 tons annually, of which Group 1 carcinogens accounted for approximately 11.3 tons. In this study, the locations of 42 industrial facilities emitting 1 kg or more of Group 1 carcinogens annually were identified using GIS. Since one industrial facility can emit multiple types of carcinogens simultaneously, duplicate counting was allowed in the analysis process. The analysis showed that 285,436 people, approximately 9.4% of the total residential population, live within a 1-km radius of Group 1 carcinogen emitting facilities. Vulnerable facilities within this radius included 28 kindergartens (7.3%), 13 elementary schools (4.8%), and 15 medical institutions (6.9%) (Fig. 3). Among the 42 industrial facilities, four emitted two types of Group 1 carcinogens simultaneously, accounting for 7.4% of the total Group 1 carcinogen emissions.

According to Lin, et al.²⁷ the lung cancer mortality risk for approximately 2 million residents living near petrochemical industrial complexes was 1.03-fold higher than that of the control group in nonresidential areas. Moreover, a 21-year follow-up study of 1 million people in Israel found statistically significant higher incidence rates of lung, breast, bladder, and prostate cancers among residents living near industrial complexes, such as petrochemical, refineries, metal processing and coating plants, fertilizer plants. The highest cancer incidence noted in groups that had resided in these areas for extended periods for 15 to 21 years²⁸.

Children are considered more susceptible to air pollutants than adults because of their increased activity levels, higher respiratory rates, and still-developing lung function. Sopian, et al.²⁹ reported higher exposure to carcinogens and increased genotoxic risk due to DNA damage in elementary school students within a 5-km radius of petrochemical industrial facilities compared to the control group. Children living near chemical complexes demonstrated a 44% increased risk of asthma attacks and a 10.3% reduction in lung capacity compared to the control group^{30,31}. These results indicate that carcinogens emitted from industrial complexes can have long-term adverse effects on the health of nearby areas, especially vulnerable groups.

Exposure concentration This study employed the air emissions of Group 1 carcinogens (formaldehyde, benzene, chromium, trichloroethylene, cadmium from industrial facilities in Incheon to the SimpleBox model to calculate the PEC_{air} at the industrial facility scale. Water emissions were only measured for formaldehyde and

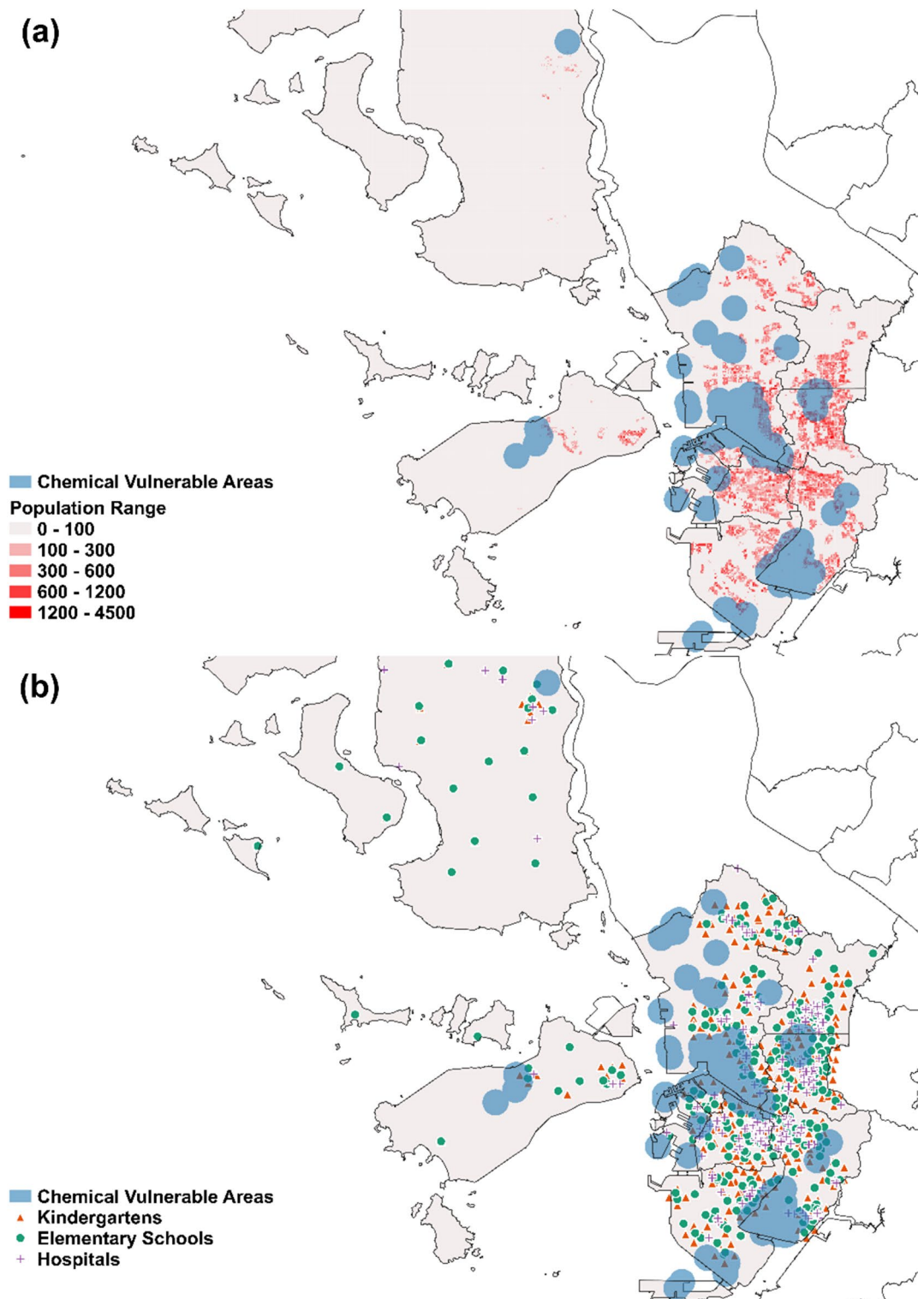


Fig. 2. Spatial distribution of areas vulnerable to chemical exposure, population ranges, and vulnerable facilities (kindergartens, elementary schools, hospitals) in Incheon. Population ranges are categorized as the number of residents per 100 m grid. Map was generated by the authors using QGIS software version 3.32 'Lima' (<https://qgis.org/>).

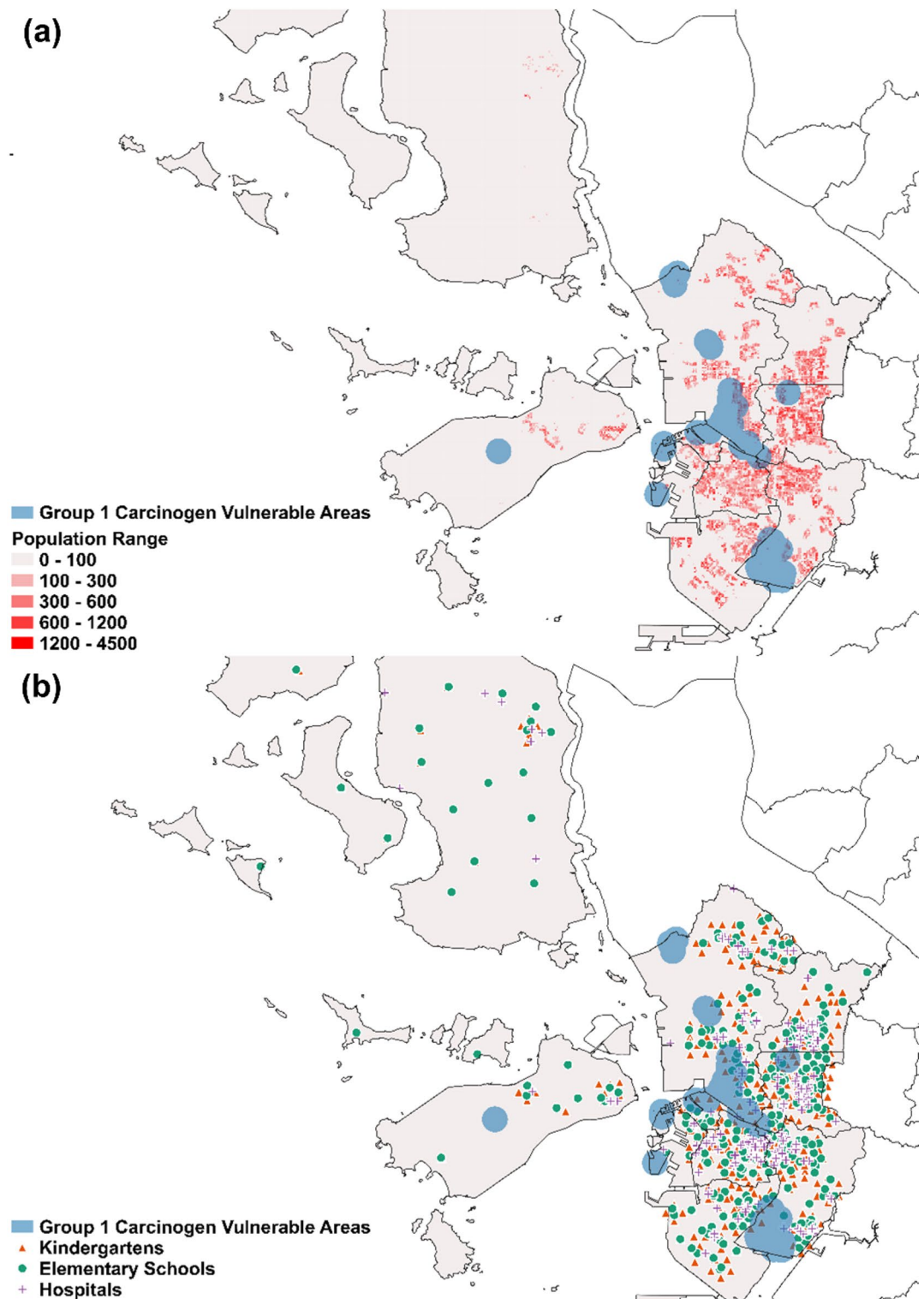


Fig. 3. Spatial distribution of areas vulnerable to group 1 carcinogens exposure, population ranges and vulnerable facilities (kindergartens, elementary schools, hospitals) in Incheon. Population ranges are categorized as the number of residents per 100 m grid. Map created using QGIS version 3.32 (<https://qgis.org/>) by the authors.

Chemical name	PEC _{air} (mg/m ³)	ADD (mg/kg-day)	CR
Formaldehyde	5.29×10^{-4}	6.22×10^{-5}	2.83×10^{-6}
Benzene	5.78×10^{-3}	6.79×10^{-4}	5.23×10^{-6}
Chromium and its compounds	5.86×10^{-3}	6.88×10^{-4}	4.33×10^{-2}
Trichloroethylene	5.66×10^{-3}	6.65×10^{-4}	9.54×10^{-6}
Cadmium and its compounds	5.71×10^{-3}	6.74×10^{-4}	4.22×10^{-3}

Table 4. Predicted environmental concentration in air (PEC_{air}), average daily dose (ADD), and Cancer risk (CR) of group 1 carcinogens emitted from industrial facilities in incheon.

chromium were confirmed to be considerably lower than air emissions; thus, they were excluded from the PEC_{air} calculation.

The PEC_{air} of Group 1 carcinogens ranged from 5.29×10^{-4} to 5.66×10^{-3} mg/m³, with the highest concentration being chromium and the lowest being formaldehyde (Table 4). Although formaldehyde had the highest emission quantity (7.29 tons/year), it exhibited one of the lowest predicted atmospheric concentrations (PEC_{air}). The result is primarily attributable to its distinct physicochemical properties. With an extremely high water solubility (400,000 mg/L) and a low octanol-water partition coefficient (logK_{ow}, 0.35), formaldehyde readily partitions into the aqueous phase rather than remaining in the air (Table S1). Combined with its high atmospheric degradation rate, these characteristics facilitate rapid removal through wet deposition and chemical transformation, resulting in a low steady-state concentration despite substantial emissions.

The average daily dose of Group 1 carcinogens for adults was calculated to be 6.22×10^{-5} to 6.88×10^{-4} mg/kg-day. This indicated that residents living near Group 1 carcinogen emitting facilities were exposed to an average of 5.53×10^{-4} mg/kg-day of carcinogens per kilogram of body weight per day. Considering that some industrial facilities emit two or more types of Group 1 carcinogens simultaneously, the actual total exposure of residents in vulnerable areas was likely to exceed the minimum value calculated in this study (6.22×10^{-5} mg/kg-day).

Cancer risk The cancer risk of Group 1 carcinogens emitted from industrial facilities in Incheon was calculated using PEC_{air} and inhalation unit risk (Table 4). The cancer risk of Group 1 carcinogens emitted from industrial facilities in Incheon ranged from 2.83×10^{-6} to 4.33×10^{-2} with formaldehyde, benzene, and trichloroethylene classified as moderate risk levels and chromium and cadmium classified as high risk levels. When compared to previous studies, the cancer risk calculated in this study for formaldehyde (2.83×10^{-6}) and benzene (5.23×10^{-6}) was similar to or slightly lower than the values reported by Chen, et al.³² for residents living near petrochemical industrial complexes in Taiwan (formaldehyde: 2.0×10^{-7} to 1.5×10^{-6} ; benzene: 2.4×10^{-5} to 6.4×10^{-5}) and the cancer risk for benzene (1.0×10^{-6} to 3.8×10^{-5}) presented by Mihankhah, et al.³³, Xiong, et al.³⁴ for Canada and China.

In numerous studies, the association between residences near carcinogen emission sources and cancer incidence rates has been reported. Santos-Sánchez, et al.³⁵ found increased lung cancer mortality in men and increased kidney cancer incidence regardless of sex among residents near industrial facilities emitting Group 1 and Group 2 A carcinogens. García-Pérez, et al.³⁶ reported significantly increased incidence and mortality rates of lung, laryngeal, and bladder cancers among residents within a 5-km radius of industrial facilities with combustion installations, noting that the actual cancer rate could be higher when considering tumor latency. The spatial analysis showed that approximately 9% of Incheon's total population resides within a 1-km radius of the identified Group 1 carcinogen emitting facilities.

Chromium (VI) is emitted from industrial activities, such as plating, welding, and chemical processes, and exists in the atmosphere as particulate or aerosol forms. Chromium inhalation exhibits carcinogenicity through increased oxidative stress, inflammatory response induction, and DNA damage in lung tissue¹⁵. A study of 500 residents in the Sukinda Valley region of India, where chromium emissions are high, identified chromium-induced diseases and observed positive reactions for oral cancer, breast cancer, and cervical cancer in 4 out of 227 individuals³⁷. In this study, the population residing within a 1-km radius of chromium emission facilities was estimated to be 5.1% (approximately 150,000 people) of the total population of Incheon, and the calculated cancer risk (4.33×10^{-2}) exceeded the EPA management standard (10^{-4}). This meant that approximately 1.86 out of 100 exposed individuals could develop cancer secondary to chromium exposure throughout their lifetime, necessitating reduction measures for these emission sources and long-term health monitoring of residents in vulnerable areas.

Cadmium is primarily emitted from metal smelting, battery manufacturing, plating, and plastic industries, and persists in the atmosphere as fine particles, entering the human body through the respiratory system. Cadmium inhalation can induce kidney damage, respiratory diseases (bronchitis, emphysema), and immune system suppression and may increase the long-term risk of developing lung and prostate cancer^{16,38}. Cadmium concentrations in the blood and urine of residents living within 2 km of plating industrial facilities in China were significantly higher than those in the control group, with increased DNA damage and kidney dysfunction markers (8-OHdG, β2-MG) and nasal degenerative conditions were observed in 26% of the study population³⁹. In this study, although the proportion of population (0.8%) and vulnerable facilities (0.7–1.4%) within a 1-km radius of cadmium emission facilities was relatively low, the calculated cancer risk (4.22×10^{-3}) exceeded the management standard, indicating the need for long-term monitoring. However, a conservative approach was used in calculating the inhalation unit risk for chromium and cadmium, based on their most toxic forms, chromium (VI) and cadmium (III). Therefore, the actual cancer risk might be somewhat lower than the estimated values.

Limitations and uncertainties of the study It is important to acknowledge the limitations and uncertainties of this study, which should be considered when interpreting the results.

First, the chemical emission data were obtained from the Ministry of Environment's Pollutant Release and Transfer Register, which relies on industry-reported estimates and may include uncertainties in actual emission quantities. Second, the SimpleBox 4.0 model operates under simplifying assumptions and default parameters that may not fully capture the environmental and meteorological conditions specific to Incheon. Third, this assessment was based on exposure factors for a general adult population, which introduces a key uncertainty. While a full quantitative sensitivity analysis was not performed, the cancer risk calculation is inherently sensitive to these exposure parameters. This is particularly relevant for vulnerable populations, such as children, who often have higher inhalation rates per unit of body weight compared to adults. As this study did not perform an age-stratified risk assessment for these susceptible groups, the presented risks may not fully represent those for all members of the community. Finally, the inhalation unit risk (IUR) values are typically upper-bound estimates designed to be health-protective, meaning the true risks could be lower. Furthermore, for substance groups like 'chromium and its compounds,' the study applied the IUR for hexavalent chromium (Cr(VI), known to be the most toxic form) to the total chromium emissions. This is a standard assumption made in the absence of toxicity data for every specific compound, but may lead to an overestimation of the actual risk.

Despite these limitations, this study provides a valuable screening-level assessment that effectively identifies areas and substances at higher potential risk.

Conclusions and policy implications

This study analyzed the emission characteristics of chemicals and carcinogens from industrial facilities in Incheon, along with the associated exposure risks to vulnerable groups in the region, leading to the following conclusions.

First, chemical emissions in Incheon revealed an overall decreasing trend after 2018 but increased again in 2021 following the resumption of industrial activities after COVID-19. This indicates that while legal regulations had an effect, changes in industrial activities can influence chemical emissions. Second, certain chemicals with high emission volumes, such as ethyl acetate, toluene, dichloromethane, and methyl ethyl ketone, are mostly emitted from a small number of large-scale facilities, indicating the need for focused emission management of these industrial facilities. Third, among the carcinogens emitted in Incheon, formaldehyde, benzene, chromium, trichloroethylene, and cadmium are Group 1 carcinogens designated by the WHO, requiring strict management. Among these, the cancer risks of chromium and cadmium exceed regulatory standards, necessitating emission reduction and continuous monitoring. Fourth, approximately 22% of Incheon citizens and numerous vulnerable facilities, including kindergartens, elementary schools, and medical institutions, are located within a 1-km radius of chemical emitting industrial facilities, raising concerns regarding human health risks. Vulnerable groups such as children and the elderly, are more susceptible to the adverse effects of chemical exposure compared to the general adult population, highlighting the need for targeted protection measures.

Based on these research findings, the following policy implications are proposed.

First, a continuous monitoring system for chemical and carcinogen emissions should be established, with strengthened emission surveys and management, especially for major industrial facilities with high emission volumes. Furthermore, support for emission reduction technology implementation and facility improvements is required to reduce emissions of high-risk carcinogens with high cancer risks. Second, further regulatory measures should be implemented to safeguard vulnerable populations residing near facilities that emit carcinogens. It is necessary to establish safety buffer zones that mandate a certain distance between emission facilities and kindergartens, schools, and medical institutions. In the long term, institutional approaches such as regulating the establishment of new chemical emission facilities near vulnerable facilities and strengthening environmental impact assessments are required. Third, to promote environmental justice, communication channels should be established between chemical-emitting facilities and local communities, alongside incentive programs encouraging businesses to voluntarily reduce emissions and cooperative initiatives that support coexistence with surrounding communities.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Conceptualization, Methodology, writing—Original Draft Preparation: Y.C., Investigation: H.K. and T.Y.J., Writing—Review and Editing, Supervision: S.D.K., Funding: S.D.K. and T.Y.J. All authors have reviewed and approved the final version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to S.D.K.

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