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Impacts of COVID-19 lockdown on $PM_{2.5}$-bound polycyclic aromatic hydrocarbons in Hohhot, Northern China: characteristics, sources, and source-specific health risks

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Abstract

Quantifying the impacts of reduction strategies on $PM_{2.5}$-bound polycyclic aromatic hydrocarbons (PAHs) is essential for reducing the health risks of $PM_{2.5}$. The COVID-19 lockdown provided an opportunity to reveal the quantitative relationship between lockdown measures and the health risks of PAHs. In this study, the characteristics, sources, and health risks of PAHs were investigated during the COVID-19 lockdown in Hohhot. The source-specific health risks of PAHs were assessed using a combination of incremental lifetime cancer risk models (ILCR) and positive matrix factorization (PMF). Compared with the pre-LD period (pre-LD, 87.41 ± 5.98 ng·m^{-3}), the total concentration of ∑PAHs during the lockdown period (LD, 32.52 ± 2.31 ng·m^{-3}) decreased by 62.8% in Hohhot. Coal combustion (51.5%), gasoline emissions (21.9%), diesel emissions (12.9%), industrial emissions (9.3%), and biomass burning (4.7%) were the predominant sources of PAHs in Hohhot. Except for male children, the ILCR of all groups exceeded the threshold for high health risks (1×10^{-4}). Dermal contact is the predominant exposure pathway for carcinogenic risk. Compared with the pre-LD period, the ILCR values decreased by 62.5–62.7% during the LD period. The PMF-ILCR results indicated that industrial emissions (29.1%), coal combustion (28.4%), and diesel emissions (18.5%) were the main sources of ∑ILCR. A Monte Carlo simulation revealed that the cumulative carcinogenic risks at the 95th percentile of the six groups were 1.5–6.3 times the threshold of high health risk (1×10^{-4}). These results emphasize that regulating industrial emissions and coal combustion is effective in reducing carcinogenic risks in industrial cities with large coal consumption.

Keywords COVID-19, PAHs, Source-specific health risks, PMF

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Introduction

Polycyclic aromatic hydrocarbons (PAHs) are the main toxic components in $PM_{2.5}$ [1, 2], which are mainly from coal combustion, industrial activities, vehicle emissions, and biomass burning [3–5]. PAHs can be classified into low-molecular-weight (LMW) (2–3 rings), middle-molecular-weight (MMW) (4 rings), and high-molecular-weight (HMW) (5–6 rings) PAHs [6]. Long-term exposure to PAHs causes persistent and irreversible adverse effects on human health [7–9]. Approximately 500 PAHs and related compounds have been detected in the air [10], and 16 have been identified as priority pollutants by the United States Environmental Protection Agency for their carcinogenicity, teratogenicity, and mutagenicity [11].

Extensive studies have been conducted on the characteristics, sources, and health risks of PAHs in Beijing-Tianjin-Hebei [12, 13], Yangtze River Delta [14], Taiyuan [6], Chongqing [15], Yuncheng [16], Xi'an [17], Xinjiang [18], Kuala Lumpur [19], Chiang Mai [20], and Portugal [21]. Few of these studies apportioned the sources of health risks. The lack of a link between sources and health risks makes it difficult to formulate effective strategies for reducing the health risks posed by PAHs [22]. The source-specific health risks of PAHs have been conducted in Huanggang [23], Tehran [24, 25], Anshan [26], Ningbo [27], and Ningxia [28] by the combination of positive matrix factorization (PMF) and incremental lifetime cancer risk (ILCR) model. The PMF-ILCR model provides a method to explore the relationship between sources and health risks of PAHs.

Since the outbreak of COVID-19 pandemic, over 170 countries have implemented government-mandated lockdown restrictions to curb its spread [29]. The lockdown measures provided an opportunity to reveal the impact of passive emission reductions on air pollutants and important information to help develop strategies to improve air quality [30–33]. However, there are few studies on PAHs during the COVID-19 epidemic. Additionally, most studies focused on the characteristics, sources, and health risks of PAHs during the lockdown (LD) period [34–37]. To our knowledge, there are no studies on the impact of lockdowns measures on source-specific health risks. The results of such studies can provide an important basis for formulating more precise strategies to control health risks. The source-specific health risks of PAHs were assessed during the COVID-19 lockdown in Hohhot to reveal the response of health risks to the control strategies. The objectives of this study were to (1) estimate the impact of the COVID-19 lockdown on the concentration of PAHs, (2) quantify the source contributions of PAHs, (3) evaluate the health risks of PAHs, and (4) quantify the source contribution of health risks posed by PAHs.

Materials and methods

Study area and sampling

Hohhot has a continental monsoon climate. It is short and hot in summer and dry and cold in winter. There are 6 months of coal-fired heating during winter. Hohhot is surrounded by the Daqing Mountain and Manhan Mountain. The semi-encircling terrain and frequent temperature inversions in winter lead to high atmospheric pollution levels. The sampling site was mainly surrounded by residential areas. Sixty-two 23 h $PM_{2.5}$ samples were collected on quartz filters (Pallflex Tissuquartz™, ϕ90 mm, USA) using medium volume air samplers (Model 2050, Qingdao Laoshan Applied Technology Research Institute, China) with a flow rate of 100 L/min from December 26, 2019 to February 28, 2020. The samples were stored at − 18 °C until analysis. Before sampling, the quartz filters were baked in a Muffle furnace at 500℃ for 4 h to remove background interference [14, 19, 38]. The concentrations of atmospheric pollutants and meteorological variables were simultaneously observed at the same site (Text S1).

Chemical analysis

The concentrations of PAHs were determined according to the Environmental Protection Standards of the People's Republic of China (HJ646-2013). The filters were cut into small pieces and extracted with 40 mL ether/n-hexane mixture (1:9 V/V) using a Soxhlet extractor for 16 h. The extraction was filtered through anhydrous sodium sulfate. The filtrate was concentrated to less than 5.0 mL using an automated parallel concentrator (ATUO EVA, Reeko, China). 5–10 mL of n-hexane was added to convert the solvent and concentrated to less than 1.0 mL. Then, 10.0 µL of 400 µg/mL internal standards (naphthalene-d_8, acenaphthene-d_{10}, phenanthrene-d_{10}, and perylene-d_{12}) were added to check the recovery rates. At last, the solution volume was fixed to 1.0 mL.

The concentrations of 16 PAHs were determined using gas chromatography/mass spectrometry (7890 A-5975 C, Agilent, USA) with an EI ion source at 230 °C. 1 µL of samples were injected with splitless mode at 280 °C. The PAHs were separated by an HP-5 MS UI column (30 m×250 µm×0.25 µm) with a flow rate of 1 mL/min. The selected ion monitoring (SIM) mode and internal standard method were used for quantification. Field blanks, replicates, and recovery rates were performed once per 10 samples. The method detection limits (MDLs), relative standard deviation (RSD) of replicates, and recovery rates were provided in Table S1. The MDLs were in the range of 0.4–0.9 ng·m^{-3}. All the concentrations of the field blanks were lower than those of the MDLs. The standard deviations of the replicates were lower than 10% (Table S1). The recoveries of the 16 PAHs ranged from 77.4 to 108%.

Positive matrix factorization (PMF)

The PMF 5.0 model was conducted to analyze the sources of PAHs in this study [28]. The principles of the PMF model were described in Text S2. The source apportionment was conducted only for the whole sampling period. The sources of PAHs during pre-LD and LD periods were not apportioned due to the limitation of data volume, which did not meet the requirements for PMF modeling. Solutions with 3–6 factors were tested to obtain an optimal solution. According to the Q values, signal-to-noise ratio, and physical interpretation of the sources, a 5-factor solution was selected (Fig. S1). Bootstrap (BS), displacement factor (DISP), and BS-DISP analyses were conducted to assess the PMF errors and rotational ambiguity (Table S2). The results of the BS, DISP, and BS-DISP analyses indicated that the model results were robust [39, 40].

Incremental lifetime cancer risk (ILCR)

The ILCR of the 16 PAHs through ingestion, inhalation, and dermal contact pathways were calculated according to Text S3. The ILCR model parameters were listed in Table S3. Monte Carlo simulation (MCS) was used to calculate the probability distribution of ILCR [41, 42]. The exposure parameters were transformed into statistical parameters using uniform or lognormal distributions [43, 44]. Sensitivity analysis was used to determine the effect of changes in the exposure parameters on the ILCR [45]. The sum of the sensitivity contributions of all the exposure parameters to the ILCR was adjusted to 100% [46]. Non-sensitive parameters were deleted from the simulation. MCS was performed for 10,000 iterations to obtain the reliability of modeling.

Results and discussion

Concentrations of PAHs

The variations in PAHs are shown in Fig. 1 and Table S4. The daily mean concentrations of $PM_{2.5}$ in the whole sampling period (WP, December 26, 2019 to February 28, 2020), pre-lockdown period (pre-LD, December 26, 2019 to January 24, 2020, http://wjw.huhhot.gov.cn/zwdt/gzdt/202001/t20200126_616767.html, last access: 2 September 2024), and LD period (January 25, 2020 to February 25, 2020, https://www.gov.cn/xinwen/2020-02/26/content_5483388.htm, last access: 2 September 2024) were 81.0 ± 57.5, 99.0 ± 64.7, and 66.0 ± 47.5 μg·m^{-3}, respectively. The concentrations of 47.7% of samples were higher than the daily mean secondary limit (75 μg·m^{-3}) of Chinese National Ambient Air Quality Standards (CNAAQS). The daily mean concentrations of ∑16PAHs during the WP, pre-LD, and LD periods were 57.86 ± 52.72, 87.41 ± 53.20, and 35.02 ± 38.04 ng·m^{-3}, respectively (Table S4). High levels of $PM_{2.5}$ and PAHs mainly occurred during the pre-LD period under unfavorable meteorological conditions (low wind speed, high relative humidity, low temperature, and prevailing southeast wind) (Fig. 2). Compared with those in the pre-LD period, the concentrations of $PM_{2.5}$ and PAHs decreased by 33.7% and 62.8%, respectively, during the LD period. This was mainly caused by the decrease in emission intensity (COVID-19 lockdown measures and higher temperatures led to lower heating intensity) and improvement in meteorological conditions (lower relative humidity and higher wind speed) (Fig. 2) [30]. The concentration of ∑16PAHs during WP period in Hohhot was significantly higher than Southern European cities [47], New York state [48], Kuala Lumpur [19], Islamabad [38], Karaj [49], and Croatia [50], whereas lower than Indian cities Durgapur [51] and Janshepur [52], compared with those of ∑16PAHs in other countries and regions (Table S5). The results indicate that developing countries are experiencing rapid economic growth and, therefore, face more serious levels of PAH pollution. The concentrations of ∑16PAHs during WP period in Hohhot were considerably higher than those in Ningxia [28], Chongqing [15], Huanggang [22], and Shanghai [53]. By contrast, the concentrations were similar to those in Xi'an [17], Yuncheng [54], and Harbin [22]. It was concluded that winter heating in the northern cities of China causes high levels of PAH pollution. The concentrations of BaP in Hohhot during the WP, pre-LD, and LD periods were 2.30 ± 2.70, 3.59 ± 3.36, and 1.10 ± 1.18 ng·m^{-3}, respectively. The daily mean concentration of BaP (3.59 ± 3.36 ng·m^{-3}) during the pre-LD period was approximately 1.44 times the daily mean secondary limit (2.5 ng·m^{-3}) of CNAAQS. The mean concentration of BaP in Hohhot was lower than that in Karaj (3.89 ± 1.28–4.09 ± 3.01 ng·m^{-3}) [49], Pakistan (3.22 ± 0.94 ng·m^{-3}) [38], Beijing (6.32 ± 10.26 ng·m^{-3}) [55], and Xi 'an (4.09 ± 2.2–6.88 ± 3.0 ng·m^{-3}) [17], whereas higher than that in America (1.5 ng·m^{-3}) [56], Molina (0.13 ± 0.19 ng·m^{-3}) [57], and Huanggang (0.80 ± 0.40 ng·m^{-3}) [22]. The concentration of BaP in Hohhot was still much higher than the expected value, especially during the pre-LD period. Therefore, further clean energy promotion, industrial boilers upgrade, industrial regulation strengthens, and transport structure improvement are needed in Hohhot.

Positive matrix factorization

The PMF source contributions and profiles for PAHs are shown in Fig. 3 and Fig. S2, respectively. Factor 1 was characterized by high levels of BaP, Ant, and Ace. BaP is a typical tracer of blast-furnace iron making [28]. Ant and Ace are commonly found in cement factories and the coking industry [58], meaning Factor 1 was identified as an industrial source. Factor 2 had high loadings for both DBA and InP. DBA and InP are typical indicators of gasoline combustion in vehicles [19, 38, 59], therefore, Factor

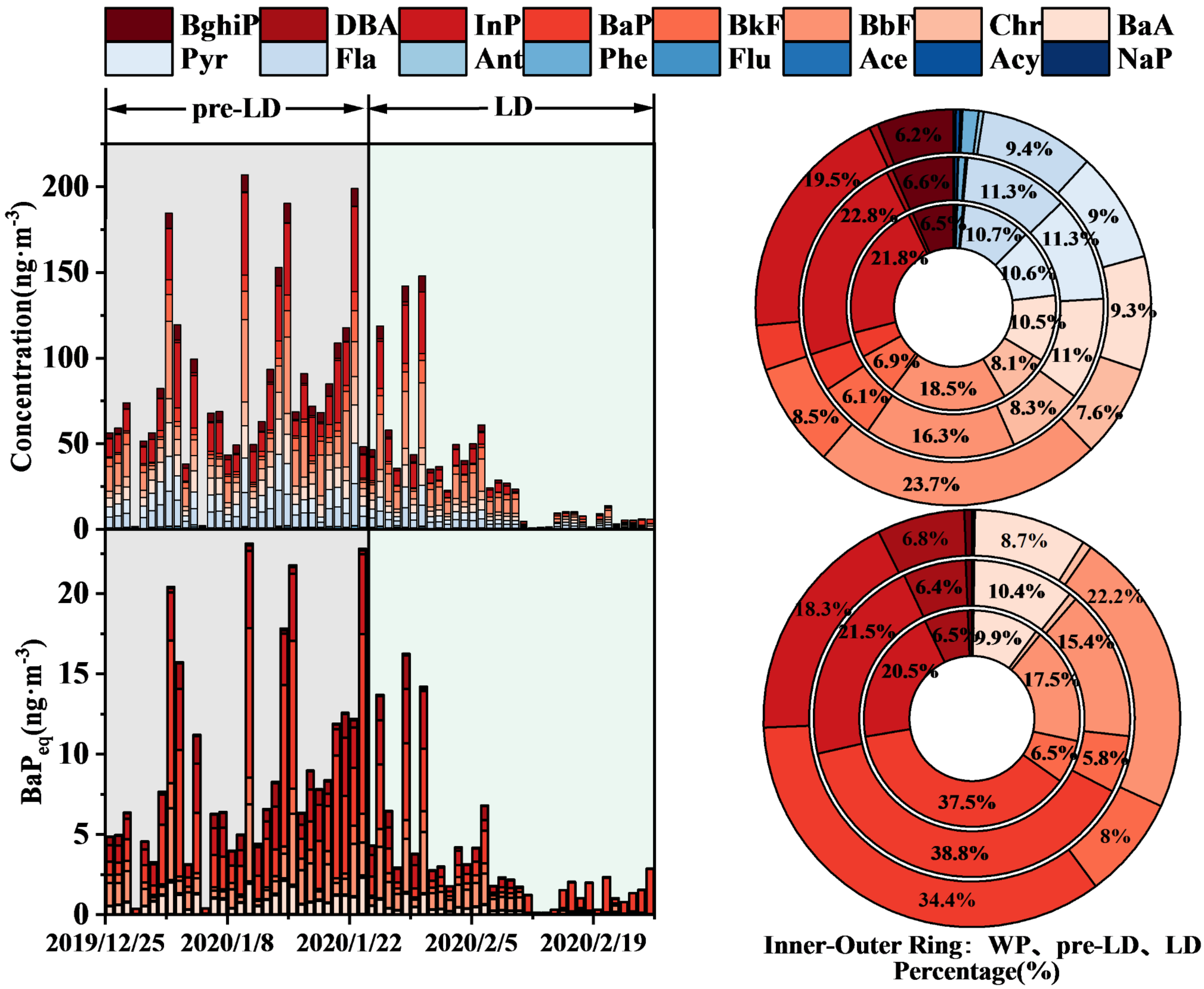

Fig. 1 Concentration, BaP_{eq}, and proportion of 16 individual PAHs

2 was identified as gasoline emissions. Factor 3 was characterized by BkF and BbF. BkF and BbF are markers of diesel-powered emissions [23], meaning Factor 3 was identified as diesel emissions. In Factor 4, Ace, Ant, NaP, Flu, Phe, and Acy had the highest loadings. NaP, ACE, and Acy are emitted from corn and wheat straw burning [54]. Ace, Phe, NaP, and Ant are the typical tracers of wood burning [17, 54, 60]. In addition, NaP and Ace may be emitted from fireworks during the Spring Festival [61]. Thus, Factor 4 was identified as biomass burning. Factor 5 was highly loaded with Fla, Pyr, BaA, and Chr and moderately loaded with Acy, NaP, Phe, InP, and BghiP. MMW PAHs, such as Fla, Pyr, BaA, and Chr are important tracers of fossil fuel combustion [23, 62]. Phe is a typical marker of coal combustion [63, 64]. NaP, Acy, and Ace are indicators of coke oven emissions [51]. Additionally, InP and BghiP have been associated with coal-fired power plant emissions [28]. Factor 5 was identified as coal combustion.

As shown in Fig. 3, coal combustion, diesel emissions, gasoline emissions, industrial emissions, and biomass burning contributed 51.1%, 21.9%, 12.9%, 9.3%, and 4.7% to the total PAHs, respectively. Coal combustion was the main source of PAHs in Hohhot, which was similar to that in Yuncheng (45.1%) [54] and Harbin (heating period) (61%) [65]. However, vehicular emission was the main source of PAHs in Huanggang (56.8%) [23], Chongqing (49.4%) [66], and Harbin (non-heating period) (59%) [65]. This could be attributed to the fact that northern cities in China consume large amounts of coal for winter heating, which emits high levels of PAHs. In the future, the emission of coal combustion can be effectively reduced through the promotion of clean fuels in the residential sector, upgrading on industrial boilers, and phasing out outdated industrial capacities.

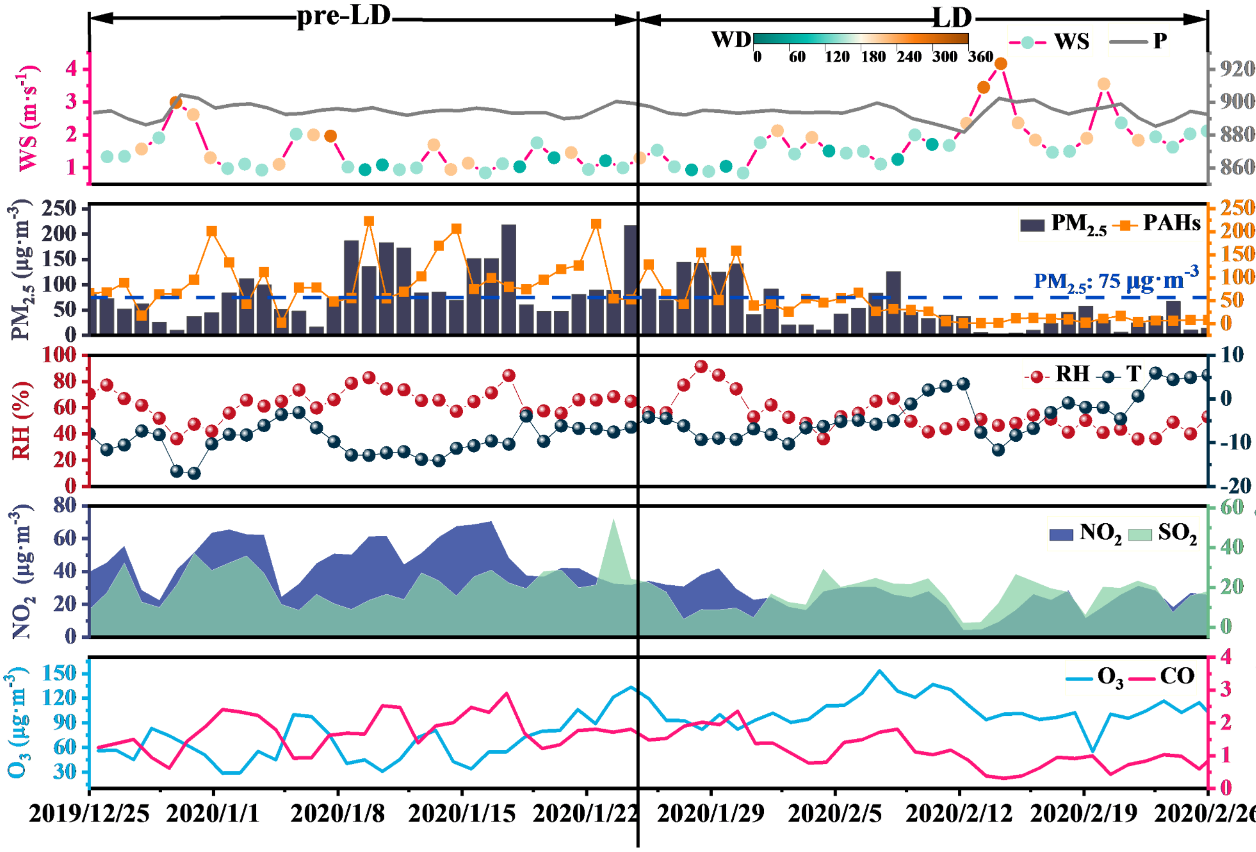

Fig. 2 Variation of PAHs, atmospheric pollutants, and meteorological parameters in Hohhot

Health risk assessment

The daily mean concentration of BaP_{eq} during the WP in Hohhot was 6.14 ± 5.94 $ng{\cdot}m^{-3}$ (0.13–23.11 $ng{\cdot}m^{-3}$). It was much higher than the global mean concentration of BaP_{eq} (0.07 ± 0.14 $ng{\cdot}m^{-3}$) [21]. BaP, InP, and BbF were the main contributors to BaP_{eq}, accounting for 37.5%, 20.5%, and 17.5%, respectively (Table S6). The concentration of seven carcinogenic PAHs (∑7CPAHs—Chr, BaA, BkF, BbF, BaP, InP, and DBA) accounted for 70.4% of the concentration of ∑16PAHs. However, their BaP_{eq} accounted for 99.1% of the total BaP_{eq}. It can be concluded that the 7CPAHs are the most important contributors to the toxicity of PAHs. As a PAH with strong carcinogenicities [67], BaP only accounted for 2.8% of ∑16PAHs; however, the contribution of BaP to the total BaP_{eq} was 37.5%. Compared with the pre-LD period, the BaP_{eq} values of Pyr, BaA, Fla, InP, BaP, DBA, and Chr decreased by more than 50% during the LD period. These PAHs are typical tracers for vehicular emissions [1, 68, 69]. The decrease in BaP_{eq} in Hohhot during the COVID-19 lockdown may be associated with the reduction of vehicular emissions and the improved meteorological conditions (from 1.38 m/s in pre-LD to 1.78 m/s in LD). Compared with the pre-LD period, the daily mean BaP_{eq} during the LD period decreased by 62.6% (Table S6). This was because of improvements in meteorological conditions (Fig. 2) and COVID-19 lockdown measures during the LD period.

The ILCR of the PAHs are presented in Fig. 4 and Table S7. The total ILCR (∑ILCR) of children, adolescents, and adults ranged from 9.97×10^{-5} to 1.03×10^{-4}, 1.11×10^{-4} to 1.14×10^{-4}, and 3.81×10^{-4} to 4.14×10^{-4}, respectively. Except for male children, the ILCR of all groups exceeded the threshold for high health risks (1×10^{-4}). During the sampling period, the ∑ILCR of the six groups were in the order of female adults (4.14×10^{-4}) > male adults (3.81×10^{-4}) > female adolescents (1.14×10^{-4}) > male adolescents (1.11×10^{-4}) > female children (1.03×10^{-4}) > male children (9.97×10^{-5}). The ∑ILCR values of females were higher than those of males in all three age groups. This is consistent with the results obtained in Urumqi [26], Yuncheng [54], India [51], and Taiyuan [26]. This may be related to women's lower body weight, larger exposed skin area, higher frequency of cooking [60], and women's lungs having a higher susceptibility to PAHs [70]. The ∑ILCR values of the three age groups were in the following order: adults > adolescents > children. The BW and SA of the children were lower than those of the adolescents; however, the ∑ILCR of the children was similar to that of the adolescents. This may be related to children's higher IR_{ing}, frequent hand–mouth activity, and high sensitivity

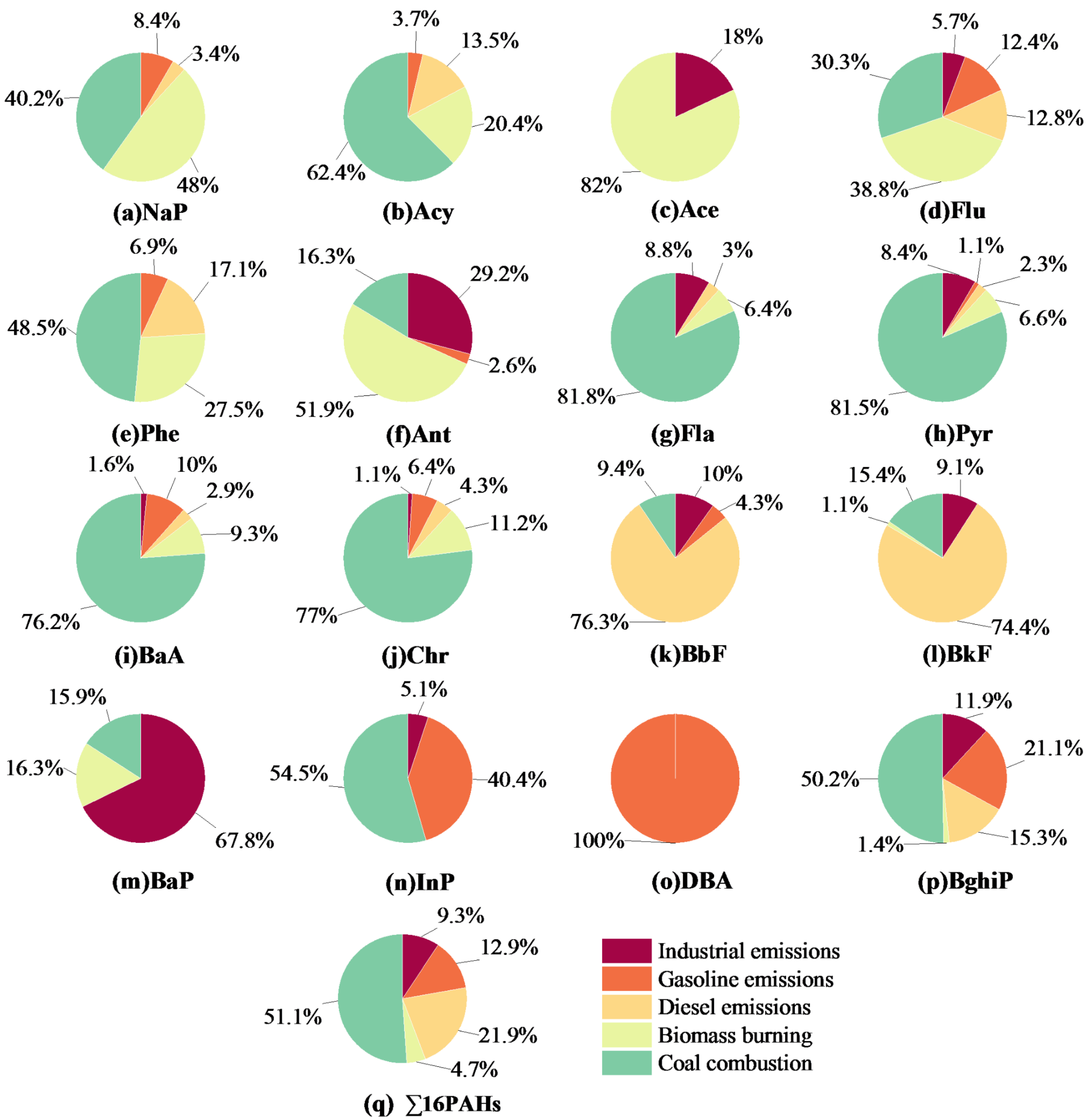

Fig. 3 Source contribution of PAHs in Hohhot

to pollutants [71]. Owing to the longer ED, adults have higher exposure doses of pollutants, leading to higher ∑ ILCR. $ILCR_{ing}$ and $ILCR_{derm}$ were considerably higher (10^{-4}–10^{-6}) than $ILCR_{inh}$ (10^{-10}–10^{-9}). $ILCR_{inh}$ can be ignored. It can be attributed to the absorption efficiency of PAHs by different pathways. The absorption of PAHs through the ingestion pathway was more efficient than that of dermal contact and inhalation [72]. The dermal absorption by skin lipids on head, hands, and arms was comparable to the inhalation pathway. Even, it would be greater than the inhalation if an entire body was counted [73]. Furthermore, clothes can sorb PAHs and may facilitate dermal intake of PAHs [74]. Thus, the ingestion and dermal contact pose higher health risks than the inhalation pathway. Similar results were reported for Mount Tai [75], Shanghai [76], Huanggang [23], and Hohhot [77]. The government should continuously prevent and suppress dust, regulate industrial emissions, and enhance the awareness of personal protection to reduce $ILCR_{derm}$. The $ILCR_{ing}$ values of children (2.80×10^{-5}) and adults

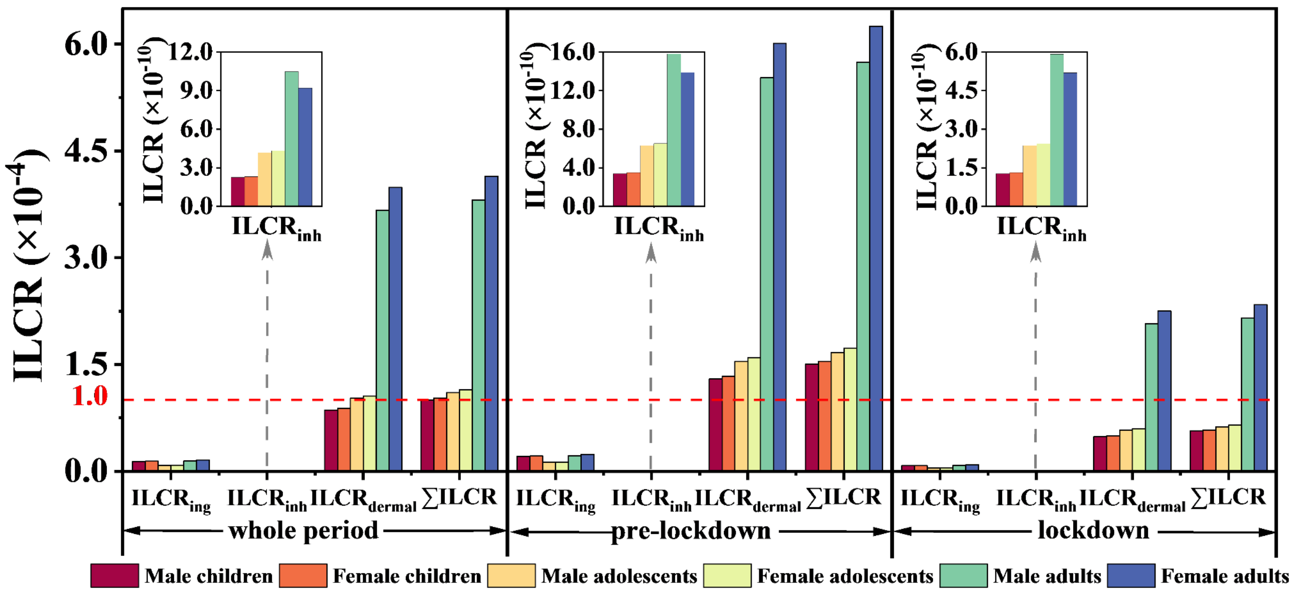

Fig. 4 ILCRs for the three exposure routes using the USEPA standard model

(3.02×10^{-5}) were approximately twice that of adolescents (1.67×10^{-5}). The $ILCR_{ing}$ of female children was close to that of male adults and much higher than that of both male and female adolescents. This can be attributed to the high frequency of hand–mouth activity, which can cause children to ingest more pollutants [78]. In addition, localized particle deposition rates in the oral cavity were similar in children and adults, whereas those in the larynx, pharynx, trachea, and bronchi were much higher in children than in adults [79], which may be another reason for the higher $ILCR_{ing}$ in children. The ILCR via the dermal contact pathway followed the order adults > adolescents > children, which may be related to the longer ED and larger SA of adults. The SA of adolescents and children were the same in the calculation; the longer ED of adolescents resulted in a slightly larger $ILCR_{derm}$ for adolescents than for children. Compared with the pre-LD period, ∑ILCR of the LD period decreased from 1.84×10^{-3} to 6.91×10^{-4}, a reduction of 62.5%. The ILCR of the 16 individual PAHs in the six groups is shown in Fig. S3. The ILCR of 7CPAHs for male children, female children, male adolescents, female adolescents, male adults, and female adults were 2.68×10^{-5}, 2.76×10^{-5}, 2.38×10^{-5}, 2.46×10^{-5}, 7.03×10^{-5}, and 7.65×10^{-5}, respectively. The contribution of 7CPAHs to ∑ILCR was as high as 94.5%, indicating that the potential carcinogenic risks of PAHs in Hohhot should not be ignored.

The MCS was conducted to assess the probability distribution and sensitivity of the relative parameters for the potential carcinogenic risk of PAHs in Hohhot. The results indicated that the cumulative probability distributions of ∑ILCR in adolescents and children were similar (Fig. 5). The ∑ILCR of adults was significantly higher than that of children and adolescents in the same percentile. Approximately 48.6%, 53.3%, 65.8%, and 70.4% of ∑ILCR exceeded 1.0×10^{-4} for male children, female children, male adolescents, and female adolescents, respectively, whereas for both male and female adults it was 100%. Most previous studies have chosen the 95th percentile as the reference health risk [66, 80, 81]. The 95th percentiles of ILCR for male children, female children, male adolescents, female adolescents, male adults, and female adults were 1.42×10^{-4}, 1.47×10^{-4}, 1.58×10^{-4}, 1.63×10^{-4}, 5.51×10^{-4}, and 5.99×10^{-4}, respectively, which were significantly higher than the results calculated by the ILCR formulas. The 50th percentiles of the ILCR values for male children, female children, male adolescents, female adolescents, male adults, and female adults were 9.91×10^{-5}, 1.02×10^{-4}, 1.09×10^{-4}, 1.14×10^{-4}, 3.77×10^{-4}, and 4.10×10^{-4}, respectively. The 50th percentile values of the ILCR from MCS were nearly equal to those of the ILCR calculation. The results suggested that PAHs in Hohhot posed non-negligible carcinogenic risks to all groups except male children.

Exposure parameters are key factors for assessing the uncertainty of health risks [82]. In this study, MCS was conducted to analyze the sensitivity of exposure parameters. The results showed that ED, AT, CSF_{derm}, SA, and ABS were the critical parameters for health risk assessment, which contributed 17.7–21.0%, 17.5–20.3%, 14.3–17.7%, 14.2–17.4%, and 13.7–16.9% to the total variance (Fig. S4). This suggested that these parameters mainly influenced the uncertainty in the health risk assessment. The localization of the sensitivity parameters (ED, SA, CSFderm, etc.) should be further studied to assess the health risks accurately.

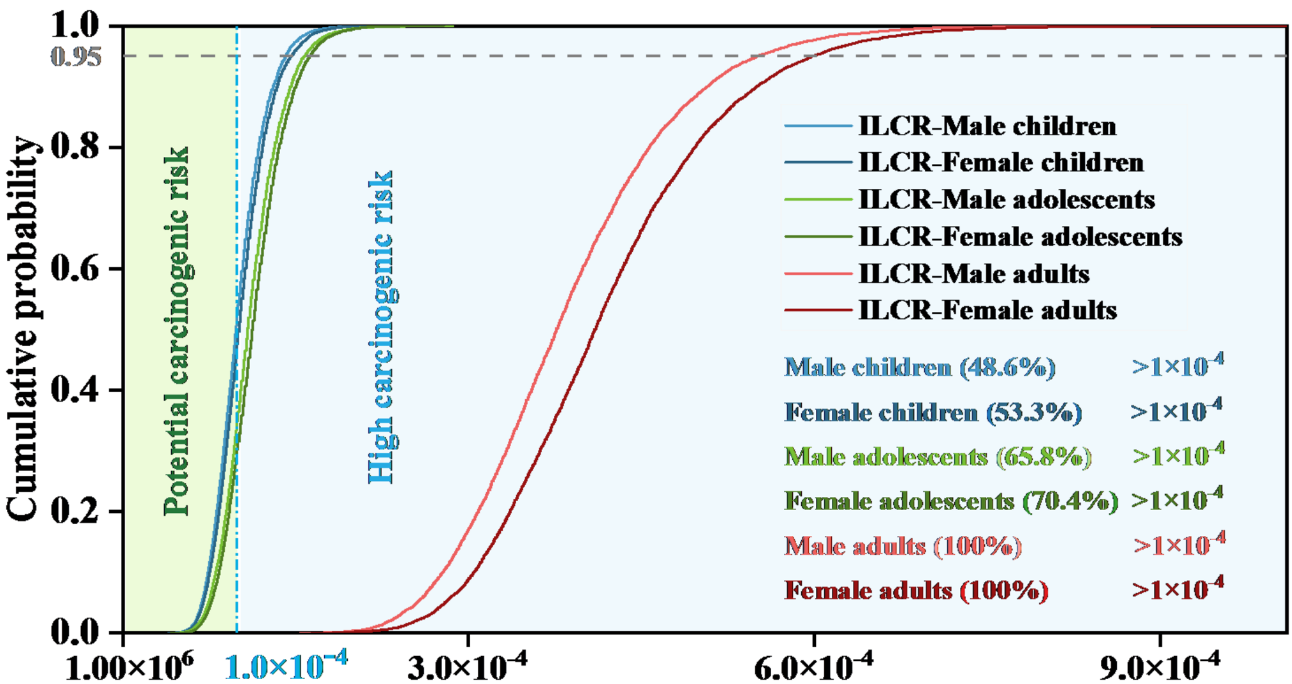

Fig. 5 Results of Monte Carlo simulation

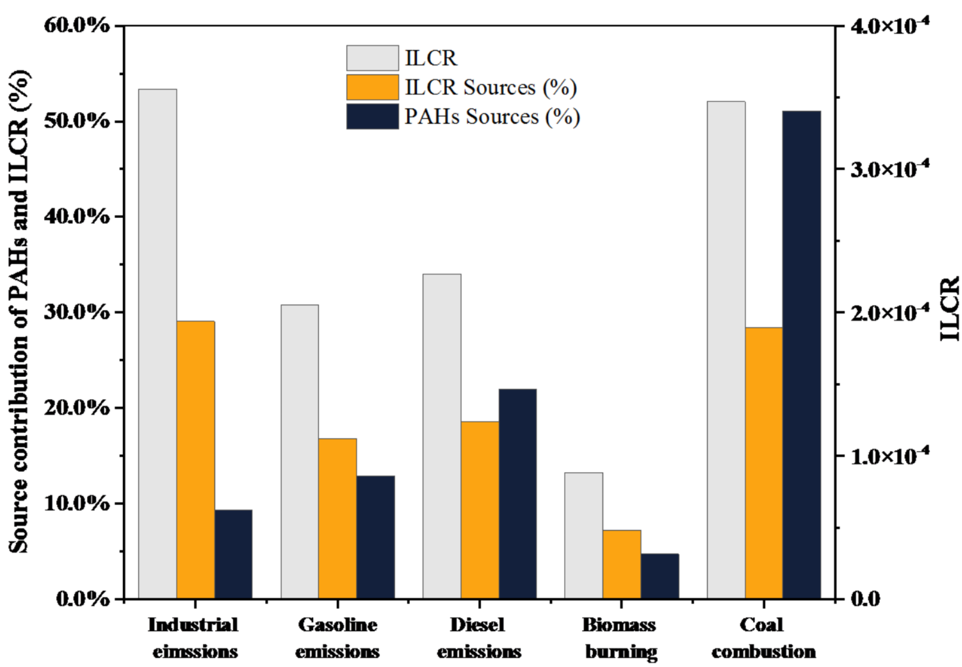

Fig. 6 Contributions of ILCR and PMF-ILCR from PAHs pollution sources in Hohhot

Source apportionment of health risk

In this study, the sources and carcinogenic risk of each PAH were estimated using the PMF and ILCR models, respectively. By the combination of PMF and ILCR model (PMF-ILCR) results, the source contribution of ILCR of PAHs in Hohhot was calculated to make health-risk mitigation strategies more targeted. The results indicated that coal combustion, diesel emissions, gasoline emissions, industrial emissions, and biomass burning to ILCR were 3.47×10^{4}, 2.27×10^{4}, 2.05×10^{4}, 3.56×10^{4}, and 8.84×10^{5} ng·m^{-3}, respectively (Fig. 6 and Table S8). Industrial emissions had the highest contribution (29.1%) to ∑ILCR, whereas they contributed less (9.3%) to PAH concentration. BaP and Ant contributed 38.4% and 16.5% to ILCR of industrial emissions, respectively (Table S9).

Coal combustion had the highest contribution (51.1%) to PAH concentration, whereas it only contributed 28.4% to ∑ILCR. This is consistent with the results in Anyang [83]. Diesel emissions had a similar contribution to ∑ILCR (18.6%) and PAHs (22.0%), which was much different from those in Ningxia [28] and Zhengzhou [83]. In conclusion, the source contributions of PAHs and ∑ILCR were quite different. Similar results have been observed in Tehran [25]. This could be attributed to the toxicity of the predominant PAHs from other sources.

Conclusions

The main objective of this study was to assess the impact of the COVID-19 lockdown on the characteristics, sources, and source-specific health risks of PAHs in Hohhot. Owing to the COVID-19 lockdown measures and the improvement in meteorological conditions, the concentrations of 16 PAHs decreased significantly from the pre-LD to LD period. The BaP_{eq} of 7CPAHs accounted for 99.1% of the total BaP_{eq}, among which BaP, InP, and BbF were the most toxic. The ILCR results indicated that the carcinogenic risks of PAHs in male children were close to the threshold of high carcinogenic risks, whereas those in the other five groups were at high carcinogenic risk levels. Compared with the pre-LD period, ∑ILCR of LD period decreased 62.5%. The PMF and PMF-ILCR results suggested that coal combustion (51.1%) and diesel emissions (22.0%) were the main sources of PAHs in Hohhot, whereas industrial emissions (29.1%), coal combustion (28.4%), and diesel emissions (18.6%) were the main sources of ILCR. This study provides a powerful approach for regulatory strategies to mitigate PAH pollution and the corresponding health risks in cities with coal-fired heating.

However, this study has some limitations. First, most of the exposure parameters of the ILCR were based on EPA, and only a few were localized. The MCS results suggested that health risk was sensitive to these exposure parameters. Second, the EF was adjusted to the winter heating period (180 days) in this study; however, using a high concentration of PAHs for 2 months to represent the entire heating period may have caused an overestimation of the ILCR. Future studies should focus on optimizing these aspects to improve the accuracy of health risk assessment.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12940-025-01161-y.

Supplementary Material 1

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Author contributions

K.J.: Data curation, Formal analysis, Validation, Visualization, Methodology, Writing - original draft. B. S.: Data curation, Formal analysis, Validation, Methodology. H. Z.: Conceptualization, Project administration, Investigation, Supervision, Validation, Visualization, Writing - review & editing. W. S.: Supervision, Methodology, Writing - review & editing. X. F., Y. S., H. R., and Y.L.: Writing - review & editing. X. C. and Z. w.: Supervision, Methodology, Writing - review & editing.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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