Pollution Levels, Sources and Risk Assessment of Polycyclic Aromatic Hydrocarbons in Farmland Soil and Crops Near Urumqi Industrial Park, Xinjiang, China

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Abstract

This study investigated the concentration, source, and risk assessment of polycyclic aromatic hydrocarbons (PAHs) in farmland soil and crops around the Urumqi Industrial Park in Xinjiang, China. The total concentration of 16 different PAHs in the soil and crop samples ranged between 2.32 and 225.11 ng/g and between 132.44 and 504.03 ng/g respectively, with average values of 39.29 ± 2.39 ng/g for the soil samples and 295.81 ± 105.00 ng/g for the crop samples. The source analysis of PAHs was performed using the positive matrix factorization and ratio method and identified the high-temperature combustion of fossil fuels, the volatilization of petroleum, coke oven emissions, and traffic emissions as main sources of PAHs in soil. The ecological risk posed by the PAHs detected in the soil samples was within a safe range. The incremental lifetime cancer risk (ILCR) value quantifies resulting from human exposure to soil containing PAH is at a safe level except for the potential carcinogenic risk to children due to ingestion exposure ($ILCRs > 1.0 \times 10^{-6}$). The ILCR posed by crops exceed 1.0×10^{-6} and the risk from sunflower crop was the highest. The highest ILCR values for each crop was observed for the adult female population. These results indicate that the farmland soil and crops near the Urumqi Industrial Park have been contaminated by PAHs and require urgent remediation to minimize adverse effects of exposure to carcinogens.

1 Introduction

Polycyclic aromatic hydrocarbons (PAHs) are persistent organic pollutants produced during the incomplete combustion of carbon-containing materials consisting of two or more benzene rings, such as wood, coal, gasoline, and diesel (Shen et al. 2011; Wang et al. 2021a). Due to their poor water solubility and good chemical stability, PAHs accumulate and persist in soil or atmosphere for a long time (Peng et al. 2011a; Yavar Ashayeri et al. 2018). PAHs in atmospheric particulate matter can further increase levels of PAHs in the soil through sedimentation. Therefore, the soil system is considered to be the main source of PAHs in the environment and affects the ecosystem and human health (Chen et al. 2017; Liu et al. 2018), and crops absorb PAHs from the soil during growth and development. PAH pollution has become a major environmental problem worldwide due to the potential carcinogenic, teratogenic, and mutagenic effects (Cao et al. 2019; Wang et al. 2017a).

With the rapid development of industry and the intensive consumption of fossil fuels, an increasing amount of PAHs are discharged into the environment. In recent years, many reports have focused on the concentration, source, spatial distribution and health risk assessment of PAHs in urban atmosphere and soil in domestic or international regions, including Chilean cities and suburbs (Apiratikul et al. 2021), Gandhi Plain (Jeba et al. 2021), North China (Liang et al. 2019), Moscow (Zavgorodnyaya et al. 2018), Iran Shiraz (Shahsavani et al. 2017), Uzbekistan (Bandowe et al. 2021), and Tianjin (Fan et al. 2021) (Jia et al. 2021; Zou et al. 2021). Although PAHs from the atmosphere and soil accumulate in crops, few researchers have investigated and analyzed this phenomenon. Diet has been identified as the main source of PAH exposure in humans, especially in non-smokers (Paris et al. 2018). Therefore, conducting sampling research on crops that are likely to be polluted by PAHs such as crops planted near industrial areas is crucial. The study and analysis of PAHs in the soil and cultivated plants near the e-waste treatment plant in Taizhou City, Zhejiang Province has shown that the three- and four-ring PAHs were easily absorbed by plants, and the higher molecular weight PAHs were prevented from being absorbed by root exudates and root bark (Wei et al. 2021). When sewage sludge is used for soil fertilization, the level of PAHs in soil increases and contributes to the excessive accumulation of PAHs in cultivated plants (Stańczyk-Mazanek et al. 2019). The average concentration of $\sum_{16}$ PAHs in four commonly consumed leafy vegetables in urban southern Nigeria ranged from 532 ng/g to 2261 ng/g (Tesi et al. 2021). In the contaminated soil and vegetable samples collected in Lagos, Nigeria, a sub-Saharan tropical environment, the total PAH concentrations in soil and vegetable samples were 200–250,000 ng/g and 100–5,000 ng/g, respectively (Adetunde et al. 2018). A study by Xiong et al. (2017) analyzed the concentration of PAHs in cabbage outer leaf, core, and root near the Shanxi large coking plant and found that the order of PAH accumulation was outer leaf > root > core. These studies show that crops are affected by the amount of PAHs in the environment that do accumulate in the crops and harm them. Xinjiang, as the central area of the “Belt and Road Initiative,” has developed rapidly in recent years, especially in heavy industries. However, research is necessary to evaluate PAHs in farmland soil and crops near industrial parks that have not been previously reported for this area.

In this study, we selected Midong Industrial Park in Urumqi as the research area to collect samples of surrounding farmland soil and important crops. The main aims of this study were: (1) to analyze the composition and pollution characteristics of PAHs in farmland soil and different types of crops, (2) to analyze the sources of PAHs in farmland soil, and (3) to assess risks associated with PAHs in farmland soils and different types of crops.

2 Research Method

2.1 Study area

The study area is located in the Midong District in the northeastern suburbs of Urumqi, northwest China. Natural disasters such as sandstorms and droughts are prevalent in this region (Simayi et al. 2018). The 216 National Highway, Dahuangshan Railway, and Petrochemical Railway pass through the boundary of the area, and the Tuwuda-Urumqi-Wukui Expressway intersects with these routes. The Midong district is rich in natural resources, including coal, siderite, limestone, petroleum, mirabilite, and other mineral resources, which has laid a solid industrial foundation (Dong and Yang 2014). These include several advantageous industries such as the chemical industry, coal and electricity, and machinery and equipment manufacturing. Highly developed transportation and industrial infrastructure release more PAHs into the environment. Urumqi is surrounded by mountains on three sides, which is not conducive to the natural dispersion of pollutants and causes them to accumulate in the environment (Li and Xie 2016; Mamtimin and Meixner 2011). In addition, the Midong district has a vast area of cultivated land and high crop yields. A significant amount of PAH present in the environment may potentially be absorbed by crops, posing health risks to humans. Therefore, the farmland surrounding the Midong Industrial Park was selected as the research area.

2.2 Sampling and preparation

From July 13 to 14, 2020, soil samples were collected from farmland near Midong Industrial Park. A total of 153 topsoil samples were collected (depth: 0–20 cm). Three soil samples (range: 2 m×2 m) were collected at each sampling site as a sample mix. According to the planting characteristics of farmers and the eating habits of citizens, eight representative crops including onion, cabbage, coriander, beans, spinach, celery, lettuce, and sunflower were collected near sampling points 2, 15, and 41. The distribution of the sampling points is shown in Fig. 1.

The collected soil and crop samples were spread in a dark basement, dried, ground in a mortar, and passed through a 100-mesh screen. Subsequently, 10 g of crop samples and 250 g of soil samples were collected, placed in opaque, white plastic bottles, sealed, and refrigerated at -2°C for subsequent experimental analysis.

2.3 Sample analysis

The analysis procedure for soil, vegetable and water samples is the same. Fifteen grams of the sample was placed in a 250-ml centrifuge tube; next, 30 ml of mixed extraction solution ($V_{\text{dichloromethane}}/V_{\text{acetone}} = 1:1$) was added to the tube and allowed to stand for 2 h. The mixture after standing is beaten for 1 min in a digital display high-speed disperser (ULTRA-TURRAX), following which, the sample was placed in a digital display water bath constant temperature oscillator (SHA-C) at room temperature (20°C) for 30 min. Then, the mixture was placed in a high-speed centrifuge (CT18RT), centrifuged at 4°C and 1000 r/min for 5 min, and 5 ml of supernatant was extracted and concentrated to near dryness. The volume was diluted to 2.5 ml with n-hexane and placed on an IKA vortex shaker (MS 3 digital) for 15 s. Finally, the sample was passed through a 0.22-μ filter membrane, waiting to assess.

An Agilent, 7890A-7000B, gas chromatograph mass spectrometer equipped with an HP5-MS column (30 m × 250 μm × 0.25 μm) was used to assess the PAH contents and composition. High-purity helium was used as the carrier gas. Splitless injection was used, and the oven temperature was maintained over the course of the experiment as follows: an initial temperature of 60°C was maintained for 1 min; the temperature was increased at a rate of 20°C/min to 180°C for 2 min, the temperature was increased at a rate of 8°C/min to 240°C for 2 min; the temperature was increased at a rate of 5°C/min to 279°C for 10 min, and finally increased at a rate of 10°C/min to 300°C for 8 min. An electron bombardment source was used for ionization and ion monitoring mode acquired data.

2.4 Quality control

The entire experimental process was conducted according to the sample recovery rate, parallel sample, sample blank, and standard addition blank for quality control. The PAHs detected in the blank samples were below the instrument detection limit as expected. The method detection limits of different samples are shown in Table 1. Tritium was added as an internal standard to measure the samples. The spiked recovery rates of the 16 PAHs in the samples ranged from 75.64–115.89%. The relative standard deviation was 3.4–9.7%. All samples were corrected for recovery, and the PAH content of the blank samples was also determined.

2.5 Source analysis method

In the source analysis of PAHs, the positive matrix factorization (PMF) method was mainly used for quantitative analysis, and the diagnostic ratio method was used for qualitative analysis.

In this study, the isomer ratios of the following PAH isomers were used to analyze the PAH pollution sources in the soil samples: FLA/(FLA + PYR), ANT/(ANT + PHE), BaA/(BaA + CHR), and InP/(InP + BghiP). A ratio analysis of the following: $ANT/(ANT + PHE) < 0.1$, $FLA/(FLA + PYR) < 0.4$, $BaA/(BaA + CHR) < 0.2$ and $InP/(InP + BghiP) < 0.2$ indicated that the main source of the PAHs was oil. The ratio $ANT/(ANT + PHE) > 0.1$ shows that the representative combustion source is also the main combustion source. The values of the ratios $FLA/(FLA + PYR) > 0.5$, $BaA/(BaA + CHR) > 0.35$ and $InP/(InP + BghiP) > 0.5$, indicate that the main source of PAHs was the burning of biomass such as grass, wood and coal; when the inverse ratios would represent the main source of PAHs being oil combustion $0.4 < FLA/(FLA + PYR) < 0.5$, $0.2 < BaA/(BaA + CHR) < 0.35$, $0.2 < InP/(InP + BghiP) < 0.5$ (Lu et al. 2019; Wang et al. 2021b).

We used the PMF model to identify the main sources of PAHs quantitatively according to the composition of the 16 different PAHs in the soil samples. The PMF model estimates the composition of pollution sources and their contribution to environmental concentrations of pollutants according to a large dataset of observations at receptor points. The basic equation of the PMF model is $X = GF + E$. This means that the matrix of the speciation sample data is decomposed into two matrix factors (Callen et al. 2014; Magesh et al. 2021): the factor contribution (G) and the factor spectrum (F). The objective function of the PMF model is expressed as follows.

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{E_{ij}}{u_{ij}} \right)^2$$

2-1

In the formula: u_{ij} is the uncertainty of the j^{th} species in the i^{th} sample; n is the number of samples; m is the number of species; E is the residual matrix, representing the difference between X and GF.

The PMF model performs iterative calculations based on the least squares method and continuously decomposes the original matrix X to obtain the optimal matrices G and F. The goal of optimization was to make Q tend to the value of the number of degrees of freedom.

2.6 Risk assessment

To evaluate the ecological risk assessment of PAHs in soil, the equivalent concentration (TEQ) of PAHs is converted from the benzo[a]pyrene (BaP) toxicity equivalence factor (TEF) which is defined as follows (Fang et al. 2004; Nadal et al. 2004; Tsai et al. 2001):

$$TEQ = \sum (PAH_i \times TEF_i)$$

2-2

To assess the possible carcinogenic risk caused by PAHs in the soil to the human body, the risk values of the three exposure pathways (ingestion, dermal contact and inhalation) were calculated according to the incremental lifetime carcinogenic risk (ILCR) model recommended by the EPA (De Miguel et al. 2007; Liang et al. 2019; Peng et al. 2011b; Qi et al. 2020; Zhang et al. 2015). The formula is as follows:

$$ILCRs_{Ingestion} = \frac{CS \times (CSF_{Ingestion} \times \sqrt[3]{\left(\frac{BW}{70}\right)}) \times IR_{Ingestion} \times EF \times ED}{BW \times AT \times 10^6}$$

2-3

$$ILCRs_{Dermal} = \frac{CS \times (CSF_{Dermal} \times \sqrt[3]{\left(\frac{BW}{70}\right)}) \times SA \times ABS \times EF \times ED}{BW \times AT \times PEF}$$

2-4

$$ILCRs_{Inhalation} = \frac{CS \times (CSF_{Inhalation} \times \sqrt[3]{\left(\frac{BW}{70}\right)}) \times IR_{Inhalation} \times EF \times ED}{BW \times AT \times PEF}$$

2-5

In the above formula, $ILCRs_{Ingestion}$, $ILCRs_{Dermal}$ and $ILCRs_{Inhalation}$ respectively, represent the lifetime carcinogenic risk caused by ingestion, dermal contact, and inhalation exposure; CS is the TEQ value of PAHs in soil (ng/g); $CSF_{Ingestion}$, CSF_{Dermal} and $CSF_{Inhalation}$ are the carcinogenic coefficients of ingestion, dermal contact and inhalation of BaP respectively. BW is the body weight (kg) of the exposed population. $IR_{Ingestion}$ is the ingestion rate (mg/day); SA is dermal exposure rate (ma/day); ABS is a carcinogen absorbed by dermal and $IR_{Inhalation}$ is the inhalation rate (m³/day). EF is the frequency of exposure (day/year); ED is the years of exposure (year); AT stands for average life expectancy (70 years or 25,550 days) and PEF is the particulate emission factor (m³/day).;

The following formula was used to evaluate the health risks to different groups of people caused by consumption of contaminated vegetables (Liao and Chiang 2006):

$$E_D = \frac{BEC \times IR \times (1 - W)}{BW}$$

2-6

$$ILCR = \frac{E_D \times EF \times ED \times SF \times CF}{AT}$$

2-7

In the above formula: E_D is the daily intake of PAHs into the human body through ingestion (ng / g • day); IR is the daily intake of vegetables (g/d); W is vegetable moisture content (%); BW is the body weight (kg); EF is the exposure frequency (365 days); ED is exposure time (years); SF was the oral slope factor of BaP (1/(mg / kg • day)); CF is the conversion coefficient (10⁻⁶ mg/ng); AT stands for average life expectancy (70 years or 25,550 days).

The corresponding parameters for calculation were selected according to the ILCR model (Peng et al. 2011a; Soltani et al. 2015). According to this model, values less than 1.0×10⁻⁶ are an acceptable risk; values between 1.0×10⁻⁶ and 1.0×10⁻⁴ indicate that there is a potential cancer risk, and when the values are greater than 1.0×10⁻⁴, it indicates that there is a high cancer risk to the human body (Maertens et al. 2008).

3 Results And Discussion

3.1 Pollution characteristics of PAHs in farmland soil and crop samples

A summary of the PAH concentrations of 51 farmland soil samples from the Midong Industrial Park is shown in Table 2. The 16 PAHs prioritized by the US EPA were all detected in the samples, and the total concentration ranged from 2.32 to 225.11 ng/g. Of all the monomeric PAHs of all the samples, the content of PHE was the highest (538.46 ng/g), followed by FLA (298.53 ng/g), and the lowest was ACY (10.82 ng/g). Compared with those in farmland soils in other regions, the average content of PAHs in the soil around Midong Industrial Park (39.29 ± 2.39 ng/g) was lower than that in East Africa Kenya (3353.04 ± 2179.81 ng/g) (Mungai et al. 2018), Shanghai (1552 ng/g) (Tong et al. 2018), Jilin (877.23 ng/g) (Chen et al. 2018) and Ningde (406 ng/g) (Zheng et al. 2019), and other regions (Ge et al. 2017). The relative molecular mass gradient of PAHs in the soil was as follows: 4 rings > 3 rings > 5 rings > 6 rings > 2 rings (Fig. 2). This was consistent with the relevant research conducted on farmland soil near an industrial zone in Nigeria (Anietie and Godwin 2016).

The concentrations of PAHs in 11 different crop samples collected around the industrial park are shown in Table 3. The PAH contents of the crop samples ranged from 132.44 to 504.03 ng/g, with an average value of 295.81 ± 105.00 ng/g. In the seven leaf crop samples, the PAH content was in the following order: Onion (504.43 ng/g) > Cabbage (363.33 ng/g) > Lettuce (357.18 ng/g) > Sunflower leaves (352.64 ng/g) > Spinach (210.69 ng/g) > Coriander (191.32 ng/g) > Celery (132.44 ng/g). There was little difference in the content of PAHs in fruit crop samples, which were beans (242.12 ng/g) and sunflower fruit (247.95 ng/g). The PAH concentration in two root crop samples were onion root (366.72 ng/g) > sunflower root (285.13 ng/g). Among the PAHs present in all the crop samples, PHE had the highest concentration, followed by FLU. BghiP was not detected in any of the crop samples. The amount of PAH present varies in different parts of the same crop. For example: PAHs in onion > PAHs in onion root, PAHs in sunflower leaves > PAHs in sunflower root > PAHs in sunflower fruit. In crop samples, the low molecular weight PAHs (≤ 4 -rings) dominate, reaching 99% of the total PAH content, while high molecular weight PAHs accounted for only 1% (Fig. 2). PAHs with more than four rings are strongly adsorbed on organic matter, and the absorption rate of plants is low (Paris et al. 2018). This was consistent with the results of previous studies (Jia et al. 2018; Wang et al. 2017b; Waqas et al. 2014).

3.2 Source analysis of PAHs in farmland soil

The PMF was used to model the data and to identify quantitatively the source of the PAHs. The PMF model identified four significant sources: the high-temperature burning of fossil fuels, oil volatilization and leakage, coke oven emissions, and traffic emissions (Fig. 3). The corresponding contribution rates were 56.2%, 10.5%, 22.8%, and 10.5%, respectively (Fig. 4). The source analysis spectrum for each factor is shown in Fig. 5.

In Factor 1, PAHs with 4 to 6 rings were dominant. The fingerprint spectra of compounds such as CHR and BaA were similar to those of PAHs emitted by coal burning in northern China (Manoli et al. 2004; Wu et al. 2014). Studies have also shown that BaA is a marker compound of natural gas combustion (Islam and Saikia 2020), and BbF, BkF, and BghiP are markers of gasoline combustion. BaA, CHR, and BbF also appear in the exhaust gas of diesel combustion (Liu et al. 2017a; Yang et al. 2013). Therefore, Factor 1 should represent the source of the high-temperature burning of fossil fuels (coal burning and transport emissions). In Factor 2, ACY and ACE accounted for a large proportion of the PAHs, followed by NAPH. Literature shows that crude oil, machine lubricants, and other petroleum derivatives are prone to produce 2–3 ring PAHs monomers such as ACY, ACE, and NAPH which is a characteristic compound of oil spills frequently used as an indicator (Dong and Lee 2009; Khairy and Lohmann 2013; Wang et al. 2006). Therefore, we infer that Factor 2 is related to oil volatilization and leakage. Factor 3 contains high levels of FLU, ANT, and PHE. Studies have shown that FLU and PHE are more common in coke oven emissions (Liu et al. 2017b; Wang et al. 2015). Therefore, Factor 3 was attributed to coke oven emissions. In Factor 4, InP and DBA accounted for a large proportion of the variance. InP is the characteristic compound indicating a diesel combustion source (Hu et al. 2017), whereas DBA is an indicator for gasoline combustion. Thus, Factor 4 represents the traffic PAH emission source.

The ratio method was used for the qualitative analysis of the PAH sources in the soil, as shown in Fig. 6. The $ANT/(ANT + PHE)$ ratios for all soil samples were greater than 0.1, except for a few sampling points, which indicates a combustion source. The $FLA/(FLA + PYR)$ ratios were greater than 0.5, and most samples had a $BaA/(BaA + CHR)$ ratio greater than 0.35, which indicates the PAH source is the combustion of grass, wood, coal, and coke. A ratio of $InP/(InP + BghiP)$ less than 0.5, indicates an oil combustion source that is usually due to transportation emissions. The ratio and PMF methods reached the same conclusion: the main sources of PAHs are oil spills, coke burning, high-temperature burning of fossil fuels, and transport emissions.

3.3 Risk assessment of PAHs in soil and crops

3.3.1 Risk assessment of PAHs in soil

By comparing the TEQ values of all the sampling points (Table 4), the BAP toxicity was still the highest in the soil samples, followed by the toxicity of DBA. However, the TEQ values of all samples were much lower than the safety value of 700 ng/g set by the Canadian government (Liu et al. 2018). The range of ILCR due to human exposure to PAHs in soil was between 1.46×10^{-10} and 1.03×10^{-5} (Table 5). The highest carcinogenic risk posed by PAHs was ingestion exposure, followed by dermal contact and inhalation exposure. The ILCR for children due to ingestion exposure to PAHs, exceeded 1.0×10^{-6} , indicating a potential carcinogenic risk to children. In the other two exposure pathways (dermal contact and inhalation exposure), the ILCR was greater for adults than that for children, but they were within safe ranges (less than 1.0×10^{-6}).

3.3.2 Health risk assessment of PAHs in crops

Daily exposure to PAHs varies greatly among different populations due to the consumption of different crops. The largest daily exposure of PAHs through ingestion was due to the consumption of sunflower ($1.08\text{--}4.25$ ng/g • kg), followed by spinach ($1.01\text{--}2.04$ ng/g • kg), and onions ($0.89\text{--}1.79$ ng/g • kg). The daily exposure due to lettuce consumption was the lowest ($0.23\text{--}0.45$ ng/g • kg) (See Table 6). The daily exposure values of different crops mainly depended on their toxic equivalents or TEQ values that were a result of the amount of PAH present in the plant material. The higher the TEQ value, the greater the exposure to PAH through ingestion. In addition, the moisture content of crops can affect the daily exposure to PAH as crops with low water content have an increased proportion of dry weight.

The ILCRs produced by different people eating different crops are shown in Table 7. Adults and children ingest all crops, all of which can pose potential carcinogenic risks (ILCRs $> 1.0 \times 10^{-6}$). Among all population groups the risk of cancer caused by the consumption of sunflowers was the highest and was greater than 1.0×10^{-6} , which indicated a potential carcinogenic risk. In addition to sunflowers (ILCRs $> 1.0 \times 10^{-6}$), teenagers eat other crops at a safe level (ILCRs $< 1.0 \times 10^{-6}$). This may be because teenagers have higher metabolisms and can rely on their bodies to digest a small amount of PAHs. The highest ILCR values of all crops were observed in adult women. It may be that adult females have higher daily exposure to crops than other groups.

4 Conclusion

The total concentrations of 16 different PAHs in soil and crop samples from farmland surrounding Midong Industrial Park in Urumqi are 2.32 to 225.11 ng/g and 132.44 to 504.03 ng/g respectively, with average values of 39.29 ± 2.39 ng/g and 295.81 ± 105.00 ng/g. In the crop samples, low molecular weight PAHs (≤ 4 -rings) were predominant. The source analysis showed that the PAHs in the soil mainly came from the high-temperature combustion of fossil fuels, the volatilization of petroleum, coke oven emissions, and traffic emissions. The ecological risk of the soil samples was at a safe level. The ILCR value due to human ingestion exposure to soil has a potential carcinogenic risk for children who were more likely to eat soil while other groups had a safe level of exposure. Regarding the ILCR value due to crops, the highest risk was due to sunflower consumption. All crops were found to have ILCR values exceeding 1.0×10^{-6} . The highest ILCR values due to consumption of crops were observed in adult female population group. In summary, PAH pollution in the farmland soil and crops near Midong Industrial Park in Urumqi was detected. The concentrations detected were above safety levels for certain crops and population groups but not all. Relevant policies should be implemented to reduce PAH pollution and prevent worsening the population groups' carcinogenic risk values.

Declarations

Competing Interests: There are no known competing financial interests or personal relationships that might affect the work described here. There are no financial interests or personal relationships that can be construed as potential competitive interests.

Author Contributions: Xi Cui: Investigation, Methodology, Conducting the experiment, Data collation and analysis, Writing - original draft. Nuerla Ailijiang: Investigation, Supervision, Conceptualization, Writing - review & editing, Formal analysis. Yusuyunjiang Mamitim: Writing - review & editing. Naifu Zhong: Assisted in the experiment. Wenhui Cheng: Helped with the sample collection. Nanxin Li: Assisted in the experiment. Qiongfang Zhang: Helped with the sample collection. Miao Pu: Helped with the sample collection.

The author confirms that the author group, corresponding author, and author order at the time of submission are correct and will not be changed later.

Ethical Responsibilities of Authors: This article is the authors' original innovative work. Neither the full text nor a part of it has been published or accepted elsewhere. It has not been submitted to any other journal, nor has it previously been submitted to the Stochastic Environmental Research and Risk Assessment.

The findings of this paper do not involve fabrication, falsification, or improper manipulation of data (including image-based manipulation). The authors followed scientifically specific rules for obtaining, selecting, and processing data.

This is a research paper that cites relevant literature to support the proposed ideas. The article does not pose a threat to public health or national security due to misuse.

The paper does not involve studies of Human Participants and/or Animals.

Informed Consent: This paper was submitted and published with the informed consent of all authors.

Data transparency Data may be obtained from the authors upon request.

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Tables

Table 1

The method detection limits (MDL) of different samples (ng/g)

Method Detection Limit—MDL	Abbrev.	Soil samples	Crop samples
Naphthalene	NAPH	0.13	0.52
Acenaphthylene	ACY	0.0061	0.15
Acenaphthene	ACE	0.0013	0.131
Fluorene	FLU	0.025	0.64
Phenanthrene	PHE	0.0064	0.12
Anthracene	ANT	0.095	0.21
Fluoranthene	FLA	0.033	0.085
Pyrene	PYR	0.041	0.11
Benzo[a]anthracene	BaA	0.019	0.071
Chrysene	CHR	0.0092	0.014
Benzo[b]fluoranthene	BbF	0.013	0.0451
Benzo[k]fluoranthene	BkF	0.015	0.018
Benzo[a]pyrene	BaP	0.0018	0.0063
Indeno[1,2,3-cd]pyrene	InP	0.0026	0.0091
Benzo[ghi]perylene	BghiP	0.0025	0.13
Dibenz[a,h]anthracene	DBA	0.0072	0.021

Table 2

Concentrations of 51 soil samples in Midong industrial zone (unit:ng/g)

Concentrations of 51 soil samples in Midong industrial zone (unit:ng/g)

(Soil Samples) PAHs	Abbrev.	Min	Max	Mean	Median	Sum	Detectable Ratio(%)
Naphthalene	NAPH	0.02	4.44	0.67	0.90	45.85	94.12%
Acenaphthylene	ACY	ND	1.10	0.19	0.21	10.82	92.16%
Acenaphthene	ACE	ND	0.95	0.38	0.39	20.03	98.04%
Fluorene	FLU	0.03	4.82	1.38	1.48	75.51	98.04%
Phenanthrene	PHE	0.81	39.76	9.98	10.56	538.46	100.00%
Anthracene	ANT	0.40	7.83	2.48	2.82	143.74	100.00%
Fluoranthene	FLA	0.04	29.64	4.87	5.85	298.53	98.04%
Pyrene	PYR	0.06	16.17	3.21	3.48	177.24	92.16%
Benzo[a]anthracene	BaA	0.02	26.34	2.53	3.55	181.12	98.04%
Chrysene	CHR	0.03	21.35	3.10	3.81	194.56	96.08%
Benzo[b]fluoranthene	BbF	0.03	18.85	2.48	3.78	192.93	98.04%
Benzo[k]fluoranthene	BkF	0.02	15.04	3.15	3.85	196.26	98.04%
Benzo[a]pyrene	BaP	0.03	12.97	1.63	2.25	114.54	96.08%
Indeno[1,2,3-cd]pyrene	InP	0.10	9.46	0.66	1.32	67.41	72.55%
Benzo[ghi]perylene	BghiP	0.68	12.93	2.16	3.02	153.78	86.27%
Dibenz[a,h]anthracene	DahA	0.07	3.47	0.40	0.60	30.51	72.55%
$\sum_{16} PAHs$		2.32	225.11	39.29	47.87	2441.29	

Annotation: ND means not detected.

Table 3

Concentrations of crop samples in Midong industrial zone (unit:ng/g)

☐Crops Samples☐ PAHs	Onion	Onion root	Cabbage	Coriander	Beans	Spinach	Celery	Lettuce	Sunflower fruit	Sunflower leaves	Sunflower root
Naphthalene	82.06	18.63	7.36	12.67	7.17	20.57	13.58	18.31	11.15	20.02	23.76
Acenaphthylene	12.71	7.67	3.94	3.54	2.44	3.21	3.25	2.98	3.37	9.30	6.84
Acenaphthene	30.05	17.59	7.42	8.69	10.11	6.36	8.61	5.35	4.52	24.11	9.43
Fluorene	109.01	79.69	38.27	27.27	26.47	26.74	20.25	26.35	29.50	44.35	34.91
Phenanthrene	208.56	181.11	225.42	96.84	136.48	106.99	60.23	222.84	135.64	178.74	152.80
Anthracene	11.95	13.31	19.93	6.83	9.46	9.37	5.10	11.97	3.48	13.89	6.55
Fluoranthene	25.49	26.36	36.06	16.33	28.80	19.39	11.84	42.27	30.01	27.47	26.86
Pyrene	15.38	15.55	19.31	11.42	14.82	10.83	5.81	21.98	23.70	23.12	18.04
Benzo[a]anthracene	1.14	0.51	0.27	0.71	0.58	0.99	ND	ND	1.33	1.46	1.07
Chrysene	3.72	4.31	3.77	4.10	3.30	2.20	1.92	4.17	3.63	4.60	3.33
Benzo[b]fluoranthene	2.08	0.70	0.13	0.60	0.39	1.33	0.59	ND	0.41	2.32	ND
Benzo[k]fluoranthene	0.54	0.58	0.36	0.77	0.70	0.84	0.43	0.55	0.65	1.51	0.69
Benzo[a]pyrene	0.53	0.12	0.32	0.43	0.45	0.32	0.20	0.05	0.07	0.59	0.31
Indeno[1,2,3-cd]pyrene	0.30	0.25	0.17	0.29	0.19	0.22	ND	ND	ND	ND	ND
Benzo[ghi]perylene	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dibenz[a,h]anthracene	0.92	0.35	0.61	0.82	0.76	1.32	0.65	0.37	0.49	1.16	0.53
	504.43	366.72	363.33	191.32	242.12	210.69	132.44	357.18	247.95	352.64	285.13

Annotation:ND means not detected.

Table 4

TEQ value of PAHs in farmland soil samples

	TEF		TEQ
NAPH	0.0010	45.85	0.05
ACY	0.0010	10.82	0.01
ACE	0.0010	20.03	0.02
FLU	0.0010	75.51	0.08
PHE	0.0010	538.46	0.54
ANT	0.0010	143.74	0.14
FLA	0.0010	298.53	0.30
PYR	0.0010	177.24	0.18
BaA	0.1000	181.12	18.11
CHR	0.0100	194.56	1.95
BbF	0.1000	192.93	19.29
BkF	0.1000	196.26	19.63
BaP	1.0000	114.54	114.54
InP	0.1000	67.41	6.74
BghiP	0.0100	153.78	1.54
DBA	1.0000	30.51	30.51
Sum			213.61

Table 5

Carcinogenic risk of PAHs in soil to different populations

	ILCR of ingestion		ILCR of dermal		ILCR of inhalation	
Different groups	children	adult	children	adult	children	adult
ILCRs	1.03×10^{-5}	8.05×10^{-6}	1.00×10^{-8}	1.05×10^{-8}	1.46×10^{-10}	6.20×10^{-10}

Table 6

Daily exposure of PAHs in crops to different populations

Daily exposure (ng/g·kg)	children		teenagers		adult	
	male	female	male	female	male	female
Onion	1.73	1.79	0.89	1.19	1.38	1.48
Cabbage	0.55	0.58	0.29	0.38	0.44	0.47
Coriander	0.95	0.99	0.49	0.66	0.76	0.82
Beans	1.68	1.74	0.86	1.16	1.34	1.43
Spinach	1.96	2.04	1.01	1.36	1.57	1.68
Celery	0.86	0.89	0.44	0.59	0.69	0.74
Lettuce	0.44	0.45	0.23	0.30	0.35	0.37
Sunflower	1.08	4.09	4.25	2.11	2.83	3.28

Table 7

Carcinogenic risk of PAHs in crops for different populations

	children		teenagers		adult	
ILCR	male	female	male	female	male	female
Onion	5.97×10^{-6}	6.18×10^{-6}	5.57×10^{-7}	7.44×10^{-7}	7.65×10^{-6}	8.20×10^{-6}
Cabbage	1.90×10^{-6}	2.00×10^{-6}	1.81×10^{-7}	2.38×10^{-7}	2.44×10^{-6}	2.60×10^{-6}
Coriander	3.28×10^{-6}	3.42×10^{-6}	3.06×10^{-7}	4.13×10^{-7}	4.21×10^{-6}	4.54×10^{-6}
Beans	5.80×10^{-6}	6.00×10^{-6}	5.38×10^{-7}	7.25×10^{-7}	7.42×10^{-6}	7.92×10^{-6}
Spinach	6.76×10^{-6}	7.04×10^{-6}	6.32×10^{-7}	8.50×10^{-7}	8.70×10^{-6}	9.31×10^{-6}
Celery	2.97×10^{-6}	3.07×10^{-6}	2.75×10^{-7}	3.69×10^{-7}	3.82×10^{-6}	4.10×10^{-6}
Lettuce	1.52×10^{-6}	1.55×10^{-6}	1.44×10^{-7}	1.88×10^{-7}	1.94×10^{-6}	2.05×10^{-6}
Sunflower	1.41×10^{-5}	1.47×10^{-5}	1.32×10^{-5}	1.77×10^{-5}	1.82×10^{-5}	1.94×10^{-5}

Figures

Figure 1

Distribution of farmland soil and crop sampling sites near Midong Industrial Park, Urumqi city (Use ArcGIS to get the graph)

Figure 2

Percentage of PAHs with different ring numbers in soil and crop samples (Use Orange to get the graph)

Figure 3

Factor fingerprint spectrum of PAHs in soil analyzed by PMF model at four factor number (Using the PMF model)

Figure 4

Contribution rate of PMF model to four sources of PAHs in soil (Use Orange to get the graph)

Figure 5

Source apportionment component spectrum of PAHs in soil under four factors by PMF model (Using the PMF model)

Figure 6

The ratio method was used for qualitative analysis of the sources of PAHs in soil (Use Orange to get the graph)