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A Study on PAHs in the surface soil of the region around Qinghai Lake in the Tibet plateau: evaluation of distribution characteristics, sources and ecological risks

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Abstract

In order to evaluate the pollution and ecological risks of polycyclic aromatic hydrocarbons (PAHs) in the soil around the Qinghai Lake, 89 surface soil samples were collected in May 2019. After ultrasonic extraction and purification of silica gel-alumina-anhydrous Na\(_2\)SO\(_4\) chromatographic column, GC-MS was used to test and analyze 16 kinds of monomer PAHs under priority control of USEPA in the samples, so as to study the distribution characteristics, sources and ecological risks. The results are shown as follows: (1) The total amount of 16 kinds of PAHs in the soil of the study area was 169.00 \(\sim\) 638.94 \(\mu\)g kg\(^{-1}\), with an average of 318.37 \(\mu\)g kg\(^{-1}\). The PAHs are dominated by dicyclic and tricyclic aromatic hydrocarbons, accounting for 40.89\%\(\sim\)70.73\% of the mass fraction of PAHs, with an average of 49.22%, and phenanthrene accounts for the highest mass fraction. (2) The percentage of sampling points that exceeded the standard (200 \(\mu\)g kg\(^{-1}\), which represents the upper limit of ‘no pollution’) was 87.6\%, dominated by mild pollution (200 \(\sim\) 600 \(\mu\)g kg\(^{-1}\)). The soil pollution in the west and south of the Qinghai Lake is relatively lighter than the north of the Qinghai Lake. (3) The toxicity equivalent concentration of TEQ\(_{\text{BaP}}\) for pyrene ranged from 8.19 to 42.35 \(\mu\)g kg\(^{-1}\), with an average of 18.82 \(\mu\)g kg\(^{-1}\). The ecological risk assessment results based on toxicity equivalent concentration and risk quality standard method showed that there was a low risk of PAHs in soil in this study area, and only a few areas exceeding the target reference value, mainly concentrated in the northern area of Qinghai Lake. (4) The results of source analysis by ratio method and principal component analysis method show that PAHs in the surface soil of the region around the Qinghai Lake come mainly from the combustion of oil and biomass.

Polycyclic aromatic hydrocarbons (PAHs) are a kind of persistent organic pollutants with strong carcinogenic, mutagenic and toxic properties that widely exist in the environment \([1\sim3]\). Specifically, 16 kinds of PAHs have been listed by USEPA (U.S. Environmental Protection Agency) as pollutants under priority control. In fact, PAHs in the environment generally arise from the incomplete combustion of organic compounds such as fossil fuels and biomass, chemical synthesis of organic polymer compounds, emission of vehicle exhaust, waste incineration, oil spill and other human activities \([4\sim7]\). PAHs can enter water and soil through dry and wet deposition, and then endanger human health by means of accumulation through the food chain \([8,9]\).

As an important ‘sink’ of PAHs in the environment, solid-phase soil medium assumes the environmental load of more than 90\% of the PAHs \([10]\). In recent years, research reports on soil PAHs in China are mainly concentrated in economically developed provincial capital cities and first-tier cities, Beijing-Tianjin-Hebei region, Yangtze River Delta and Pearl River Delta \([11,12]\). However, there are few studies on the regions with
poor environment and less developed economy such as polar regions, high mountains and plateaus. Due to the atmospheric movement and the semi-volatile nature of PAHs, remote areas such as polar regions and high mountains can also be polluted by PAHs [13, 14]. Located in the northeast of the Qinghai-Tibet Plateau, the Qinghai Lake is known as China’s largest inland lake, with an average altitude of 3196 m. It is the intersection area of the arid region in the northwest, cold region in the southwest and monsoon region in the east of China, which has a typical plateau continental climate [15–17]. In recent years, with the development of social economy and tourism in the region around the Qinghai Lake, increasingly more frequent human activities have affected the native environment of the Qinghai Lake. By studying the content and distribution characteristics of PAHs in surface soil of Qinghai Lake area, this paper further analyzed the source of PAHs and evaluated the potential ecological risks. And the purpose is to provide theoretical basis and scientific support for the prevention and control of regional pollution so as to better utilize and develop the tourism resources of Qinghai Lake.

1. Materials and methods

1.1. Sample collection
In May 2019, samples were collected in the region around the Qinghai Lake according to the grid method. A sampling point was set for every 5 km or around on average, with the auxiliary of GPS, and the longitude and latitude of sampling points were accurately recorded. A total of 89 soil samples were collected (as shown in figure 1). In each sampling point, the diagonal multi-point sampling method was used to collect samples of surface soil (0 ~ 20 cm) and mix them evenly, and then the collected soil samples were placed in aluminum boxes and transported to the laboratory without delay. After the samples were naturally air dried, it is necessary to remove grass roots, gravels and other sundries, grind the soil samples with a 100-mesh sieve and then freeze them for preservation. In this paper, 16 kinds of PAHs under priority control as listed by USEPA are tested: naphthalene (Nap), acenaphthylene (Ace), acenaphthene (Acy), fluorene (Flu), phenanthrene (Phe), anthracene (Ant), fluoranthene (Fla), pyrene (Pyr), benzo [a] anthracene (BaA), chrysene (Chr), benzo [b] fluoranthene (BbF), benzene [K] fluoranthene (BkF), benzo [a] pyrene (BaP), benzo [1, 2, 3-c, d] pyrene (InP), diphenyl [a, h] anthracene (DahA) and Benzo [g, h, i] pyrene (BghiP).

1.2. Analysis method
The reagents and utensils used for the experiment in this paper include pure hexane and dichloromethane for analysis; pure anhydrous Na₂SO₄ for analysis, which were dried for 4 h at the temperature of 450 °C in a muffle furnace; quartz sand (20-mesh), which were used after being cooled for 4 h in the muffle furnace; chromatography silica gel (200-mesh), which were activated for 16 h at the temperature of 130 °C before use. In fact, the above reagents were purchased from Sinopharm Group Chemical Reagent Co. Ltd, while the standard

![Figure 1. Distribution Diagram of Sampling Points for Surface Soil in the Region around the Qinghai Lake.](image_url)
solutions of 16 kinds of PAHs, recovery indicators, such as Nap-d8, Ace-d10, Phe-d10, Chr-d12 and Pyr-d12 were purchased from O2Si.

In this paper, PAHs were analyzed by gas chromatography-mass spectrometer (GC-MS QP2010, manufactured by Shimadzu), and the samples were pretreated by ultrasonic extraction and chromatography before determination. The working conditions for determination were as follows: The chromatographic column was a quartz capillary column (HP-5 MS, 30 m × 0.32 mm × 0.25 μm); the injection port temperature was 280 °C, the purge flow rate was 3 ml/min, the column flow rate was 1.8 ml/min, unsplit stream sampling was adopted for 1.0 min, and the injection volume was 1 μL. The programmed temperature rise conditions were as follows: The initial temperature was 70 °C (2 min), which were increased to 180 °C at the rate of 20 °C/min and held for 5 min, and then were increased to 290 °C at the rate of 10 °C/min and held for 10 min. The interface temperature was 290 °C, and the ion source temperature was 230 °C.

In this paper, source analysis was used to trace the source of PAHs in soil. Principal component analysis (PCA) can screen out the main independent synthesis factors from the system of high dimensional variables, which not only retain the original main information, but also make each other mutually uncorrelated [18]. The ratio method reflects the source of PAHs through the ratio of high-ring to low-ring PAHs [19]. Therefore, these two widely accepted and used source analyses were selected as the means of source analysis for PAHs.

1.3. Quality assurance and quality control
In order to ensure the reliability of the experimental method and the accuracy of the experimental data, blank, blank labeling, matrix labeling and sample parallel are used in the experiment to achieve quality control and assurance. In the process of sample pretreatment, a blank, blank labeling and matrix labeling are added for every 12 samples. The blank labeling recovery of samples ranges from 61.48% to 118.69%, the matrix labeling recovery of samples ranges from 62.69% to 119.72%, and no target pollutant is detected in the blank samples. According to the detection limit calculated according to the method three times of the SNR, the detection limit calculated according to the method of 16 kinds of PAHs is 0.3–35 μg·kg⁻¹.

2. Results and discussion

2.1. Content and composition characteristics of PAHs in soil
In table 1, it can be seen that the total amount of 16 kinds of PAHs (∑₁₆PAHs) of 89 soil samples ranges from 169.00 to 638.94 μg·kg⁻¹, with an average of 318.37 μg·kg⁻¹. From the perspective of monomer PAH, the content ranges from 0.3 to 215.17 μg·kg⁻¹, among which that of Phe is the highest, accounting for 22.83% of the total; followed by Fla and Pyr, accounting for 10.58% and 9.60%, respectively, while that of DahA is the lowest, with an average of 3.61 μg·kg⁻¹, accounting for 1.18% of the total. In the study area, the content of monomer PAH in the surface soil is sorted as follows: Phe>Fla>Pyr>Nap>Flu>Chr>BbF>Acy>BaA>BaP>BghiP>BkF>InP>Ant>Ace>DahA.
PAHs can be divided into three categories by the number of benzene rings in the chemical structure: i.e. low ring (2–3 rings), middle ring (4 rings) and high ring (5–6 rings), and their contents are shown in figure 2. It can be seen from the figure that the content of low-ring (2–3 rings) PAHs in the surface soil samples in the region around the Qinghai Lake accounts for 40.89%–70.73%, with an average of 49.22%; that of 4-ring PAHs...


2.2. Pollution level and spatial distribution characteristics of PAHs in soil

According to Maliszewska-K et al. [20], the pollution of PAHs in the soil is divided into 4 grades, i.e. no pollution ($\sum$16 PAHs $< 200 \, \mu g \, kg^{-1}$), mild pollution (200 $\sim$ 600 $\mu g \, kg^{-1}$), moderate pollution (600 $\sim$ 1000 $\mu g \, kg^{-1}$) and severe pollution ($> 1000 \, \mu g \, kg^{-1}$). In this paper, the content of PAHs in only 11 out of 89 sampling points is less than 200 $\mu g \, kg^{-1}$, belonging to no pollution, for 12.4%; the pollution of PAHs is found in the other 78 sampling points, which is dominated by mild pollution, and the content of PAHs in sampling points No. 71 and No. 73 only is found to exceed 600 $\mu g \, kg^{-1}$, reaching the level of moderate pollution (figure 3). On the whole, the surface soil in the region around the Qinghai Lake has been significantly polluted by PAHs, and the pollution in some areas tends to be severe, which needs to be concerned. The northern shore area of Qinghai Lake (sampling points No. 49 $\sim$ 79) had the highest content of PAHs in soil, with an average value of 350.30 $\mu g \, kg^{-1}$ (figure 3). Specifically, the content of PAHs in sampling points No. 71 and No. 73 located on the north bank of the lake was more than 600 $\mu g \, kg^{-1}$ (figure 3), reaching the level of moderate pollution. One reason is that the north shore of the lake is relatively developed in tourism and densely populated. And the second reason is that the sampling site is not far from the township. On the whole, it is greatly affected by traffic pollution sources. In addition, the two sample sites were collected from the rapeseed field in Ha’ergai town, which may be greatly affected by the residual organic pollutants. In the south bank of the Qinghai Lake (sampling points No. 16 $\sim$ 33), it is also subject to mild pollution on the whole, and the average content of PAHs in the soil is 336.94 $\mu g \, kg^{-1}$ (figure 3). As the sampling points on the south bank are close to G109 (which is the major highway connecting Tibet and Qinghai province), the soil is greatly affected by traffic sources, which also causes the pollution to a certain degree. On the east bank (sampling points No. 1 $\sim$ 15) and west bank (sampling points No. 34 $\sim$ 48) of the Qinghai Lake, the overall pollution level is significantly declined. In the sampling points on the west bank, the average content of PAHs is 266.57 $\mu g \, kg^{-1}$; in the sampling points on the east bank, that is 260.63 $\mu g \, kg^{-1}$ (figure 3). In addition, there are a large number of sand dunes in the lakeside area of the eastern part of the Lake, where is subject to less interference of crop and pasture production, while the eastern part of the Lake is far away from major highways, with a high coverage of grassland vegetation.

In order to compare the difference between the soil in the study area and that in other areas at home and abroad in the content of PAHs, relevant information and data has been collected, compared with other areas (as shown in table 2), it can be found that the content of PAHs in the surface soil of the study area is much lower than that in the surface soil of urban areas in Miami [21], Beijing [22], Quanzhou [23], Shenzhen [24] and other cities and the vegetable field in Greece’s Thessaloniki Industrial Area; but it is obviously higher than that in the surface soil of the Yangtze River Delta [12], soil of the farmland in Chongming Island, Shanghai [25] and surface soil in the North-central Lake Basin of the Qinghai-Tibet Plateau [26] and the central area of the Qinghai-Tibet Plateau [27]. In fact, it also indicates that the content of PAHs in the surface soil of the study area has already been at a higher level, which not only has exceeded that of other areas in the Qinghai-Tibet Plateau, but even has exceeded that of the Yangtze River Delta where is industrially and economically developed, so the potential ecological risks are worthy of attention.

### Table 2. Comparison of PAHs in surface soil of Qinghai Lake with Other Areas.

| Research area | Soil type             | Content ($\mu g \, kg^{-1}$) | Average content | Literature |
|---------------|-----------------------|-----------------------------|-----------------|------------|
| Central Tibetan Plateau, China | Urban and Suburban | 0.43 $\sim$ 26.7 | —                | [27]        |
| Qinghai Tibet Plateau Lake Basin, China | Surface soil | 60.6 $\sim$ 614.0 | 294              | [26]        |
| Qinghai Lake area, China | Surface soil | 169.0 $\sim$ 638.94 | 318.37          | This study  |
| Beijing, China | Urban               | 219.0 $\sim$ 27825.0 | 3917            | [22]        |
| Chongming Island, Shanghai, China | Farmland soil | 24.9 $\sim$ 1014.6 | 192.8           | [25]        |
| Quanzhou, China | Urban               | 28.2 $\sim$ 1432.3 | 408.8           | [23]        |
| Shenzhen, China | Urban               | 5.0 $\sim$ 7989.0 | 417             | [24]        |
| Yangtze River delta, China | Urban               | 21.0 $\sim$ 3578.5 | 310.6           | [12]        |
| Thessaloniki, Greece | Industrial zone | 38.0 $\sim$ 2244.0 | 707             | [28]        |
| Miami, USA     | Urban               | 1508.0 $\sim$ 2364.0 | 1869            | [21]        |

Note: $^-1$ means no data available

accounts for 17.04% $\sim$ 38.10%, with an average of 31.06%; that of 5 6 ring PAHs accounts for 9.58% $\sim$ 33.40%, with an average of 19.72%. It can be seen that PAHs in the surface soil of the study area are dominated by low-ring PAHs, but the proportion of low-ring PAHs in sampling points No. 25, No. 43, No. 48, No. 70 and No. 84 is similar to that of high-ring PAHs.
2.3. Ecological risk evaluation of PAHs in soil

In this paper, the pollution of monomer PAH is evaluated with reference to Holland’s soil quality standard (table 1). It’s worth pointing out that since China currently has no clear limit on the content of PAHs in soil, the Dutch standard is adopted here. More importantly, the Netherlands is selected because it has a long reputation in soil remediation practice, and which can provide us with great reference value in the soil remediation and treatment in China. The results show that 4 out of 16 monomer PAHs in the study area have an exceeding standard rate of more than 50%, which are Fla (93.26%), Nap (89.89%), Phe (70.79%) and Chr (56.18%), respectively. In addition, BaA and BaP also have a different point exceeding the standard phenomenon. BaP is highly toxic [29] and can seriously pollute the soil. Therefore, it can be seen that the surface soil of the region around the Qinghai Lake has been polluted by PAHs to a certain degree.

In order to further evaluate the ecological risks of PAHs, the total toxic equivalent quantity (TEQBap) [30] of PAHs in the samples is calculated based on Bap [30], which has been widely used. In order to normalize the contribution of monomer pollutant to the total toxic equivalent quantity, the toxic equivalent quantity factor of BaP is used to study the toxicity of monomer PAH in soil. As the first discovered monomer PAH with the highest carcinogenicity, BaP is used as reference in the method, and its TEF is set to 1. The calculation formula is as follows:

$$TEQ_{ BaP } = \sum (C_i \times TEF_i)$$

Where, $C_i$ refers to the mass concentration of each monomer PAH (μg·kg$^{-1}$); TEF$_i$ refers to the corresponding toxic equivalent quantity factor (as shown in table 1).

In this study, the total toxic equivalent quantity of 89 soil sampling points is shown in figure 4. The results show that the TEQBap of soil samples in the study area ranges from 8.19 to 42.35 μg·kg$^{-1}$, with an average of 18.82 μg·kg$^{-1}$. That of 7 carcinogenic PAHs ranges from 7.94 to 41.64 μg·kg$^{-1}$, with an average of 18.45 μg·kg$^{-1}$, accounting for 98.03% of the total TEQBap, which indicates that these 7 carcinogenic PAHs are the major contributor to the total TEQBap. Specifically, BaP contributes the most to TEQBap, followed by BghiP. In sampling points No. 33, No. 58, No. 71, No. 73, No. 74, No. 78 and No. 89, the TEQBap exceeds the standard reference value (i.e. 33 μg·kg$^{-1}$), accounting for 7.87% of the total sampling points, that in sampling point No. 71 is the highest, i.e. 42.35 μg·kg$^{-1}$, which is 1.3 times that of the standard reference value. In terms of the distribution of sampling points exceeding the standard, the sampling points with the value of TEQBap exceeding the standard reference value are mainly concentrated in the northern part of the Qinghai Lake, so that certain control and treatment measures shall be taken. As for the remaining 92.13% of the soil samples, the toxic equivalent quantity of BaP is lower than the standard reference value, belonging to the level without ecological risk. As for samples No. 4, No. 19, No. 34, No. 52 and No. 56 in the sampling points of the southern and northern study area, the toxic equivalent quantity of BaP is lower than 10 μg·kg$^{-1}$, which is much lower than the standard.

![Figure 4. Toxic Equivalent Quantity of BaP in the Surface Soil of the Region around the Qinghai Lake.](image-url)
reference value, belonging to relatively safe area. In addition, the value of $\text{TEQ}_{\text{Bap}}$ in sampling points No. 13, No. 28, No. 61 and No. 77 is close to the standard reference value, which requires attention and prevention.

Combined with the field investigation, the potential causes of $\text{TEQ}_{\text{Bap}}$ distribution in soil samples were analyzed according to the land use pattern in the study area. In the east and west of the lake, the land use pattern is mainly grassland, with occasional bare sand and sandy beach. In the eastern part of the lake, vegetation is lush and reclamation efforts are not strong, so it is mainly the original ecological environment. And the southern part of the lake is dominated by pastures and grasslands with many agricultural and animal husbandry industry activities. The northern part of the lake is dominated by farmland, grassland and tall thatch. Due to the good natural scenery in the northern part of the lake, the tourism industry is well developed, with numerous tourists, frequent floating population activities and much vehicle traffic. Therefore, the northern part of the lake is the most polluted and the ecological risk level is high.

2.4. Source analysis of PAHs in soil

2.4.1. Ratio method

The composition and source of PAHs are complex, so it is generally considered that low-ring ($2 \sim 3$ rings) PAHs come mainly from the incomplete combustion of fossil fuels and leakage of oil products, while middle and high-ring ($4 \sim 6$ rings) PAHs come from the high-temperature combustion of fossil fuels and wood [31]. Therefore, the relative abundance of PAHs rings can be used to determine whether PAHs originated from pyrolysis or petroleum pollution. In fact, the ratio of high-ring and low-ring PAHs ($\Sigma \text{LMW}/\Sigma \text{HMW}$, later referred to as 'LMW/HMW') is usually deemed as an indicator of the source of PAHs. Generally speaking, when LMW/HMW is smaller than 1, it indicates that PAHs come mainly from the combustion source, while when LMW/HMW is greater than 1, it indicates that PAHs come mainly from oil pollution [32].

In the study area, the $\Sigma \text{LMW}/\Sigma \text{HMW}$ of soil samples ranges from 0.69 to 2.42, with an average of 0.99, indicating that PAHs in the surface soil of the region around the Qinghai Lake come mainly from the combustion source. In addition, the method of isomer ratio analysis is one of the primary methods for identifying the source of PAHs. It uses the isomer ratio in PAHs, such as $\text{Fla}/(\text{Fla+Pyr})$, $\text{BaA}/(\text{BaA+Chr})$, $\text{Inp}/(\text{Inp+BghiP})$ and $\text{Ant}/(\text{Ant+Phe})$, to trace the source of PAHs in the environment [33, 34]. According to Yunker et al [35], it is considered that when $\text{BaA}/(\text{BaA+Chr})$ is smaller than 0.2, the pollution of PAHs comes mainly from the oil source; when $0.2 < \text{BaA}/(\text{BaA+Chr}) < 0.35$, the pollution source is the mixture of oil and combustion sources; when $\text{BaA}/(\text{BaA+Chr})$ is greater than 0.35, it comes from the combustion source of biomass and coal, if $\text{Inp}/(\text{Inp+BghiP})$ is smaller than 0.2, it indicates the oil source; when $0.2 < \text{Inp}/(\text{Inp+BghiP}) < 0.5$, it mainly comes from the oil combustion source; when $\text{Inp}/(\text{Inp+BghiP})$ is greater than 0.5, it means that the combustion of biomass and coal is the main source.

Figure 5. Isomer ratio analysis of PAHs in the surface soil of the region around the Qinghai Lake.
2.4.1.1. Method of isomer ratio analysis
In this paper, the ratios of BaA/(BaA+Chr) and Inp/(Inp+BghiP) with the same molecular weight and thermodynamic stability are selected to determine the source of PAHs. The results show that the ratio of BaA/(BaA+Chr) in all sampling points is greater than 0.2 (as shown in figure 5), specifically, the ratio of BaA/(BaA+Chr) in 33.7% of the sampling points is greater than 0.35, and that in 66.3% of the sampling points is between 0.2 and 0.35, which indicates that most of PAHs in the soil of the region around the Qinghai Lake comes from the mixed oil and combustion sources, while a small part comes from the combustion source of biomass and coal. The ratio of Inp/(Inp+BghiP) in 46.1% of the sampling points is greater than 0.5, which reflects the source of coal and biomass combustion, mainly ranging from 0.4 to 0.6, indicating that the source is mainly the combustion source composed of the combustion of oil, coal and biomass. To sum up, the pollution of PAHs in the soil of the region around the Qinghai Lake mainly comes from the source of coal, biomass and oil combustion, which is consistent with the results expressed in the LMW/HMW ratio.

2.4.2. Principal component analysis
In order to explain the source of PAHs in the soil of the study area more accurately, SPSS21.0 software is used to conduct principal component analysis (PCA) on the PAHs of 89 samples, and 3 principal components are analyzed and extracted, with a characteristic root of greater than 1 and a cumulative variance contribution rate of 72.45% (as shown in table 3). It can be seen from table 3 that the cumulative variance contribution rate of 3 factors extracted in each sampling point is above 70%, which can reflect all information in an all-round way, indicating that it is feasible to use these 3 factors to analyze the source of PAHs. The variance contribution rate of principal component 1 is 31.89%, in factor 1, Phe, BaA, Chr, BbF, BkF, BaP, InP and BghiP have a higher load, with the load factors of 0.610, 0.718, 0.751, 0.727, 0.704, 0.767, 0.766 and 0.682, respectively, and these components are mainly the PAHS with 5–6 rings. Phe and Chr indicate the coal combustion source, BaA, BbF, BkF and BaP stand for fuel source, while InP and BghiP indicate the combustion of gasoline and diesel, and BaA, BbF, BaP, InP and BghiP indicate vehicle exhaust emissions [36]. The representative substance (Fla) of principal component 1 and low-ring crude oil or coking by-product (Nap) and characteristic substance of biomass combustion (Acy) have a low load. Therefore, principal component 1 indicates that one of the sources of PAHs in topsoil is traffic pollution source. PC2 explains the 25.85% of the overall change in the data matrix, and has a higher load together with components Nap, Ace, Flu, Fla and Pyr, in fact, Flu, Fla and Pyr are usually the characteristic effluents of oil source [37], that is, the oil is leaked and enters the soil in the mining and transportation process. Some studies show that the low-temperature combustion of wood and biomass also releases a large number of Nap [38], so principal component 2 mainly reflects the oil pollution source and biomass combustion emission. In PC3, Acy and Ant have the highest load, of which Acy indicates the biomass combustion source, while Ant mainly comes from incomplete combustion of wood or diesel oil, demonstrating

| PAHs    | Principal factors |
|---------|-------------------|
|         | 1     | 2     | 3     |
| Nap     | 0.197 | 0.886 | 0.030 |
| Acy     | 0.086 | 0.034 | 0.902 |
| Ace     | 0.091 | 0.901 | 0.060 |
| Flu     | 0.112 | 0.907 | 0.064 |
| Phe     | 0.610 | 0.452 | −0.103|
| Ant     | 0.303 | −0.081| 0.872 |
| Fla     | 0.523 | 0.638 | −0.157|
| Pyr     | 0.521 | 0.676 | −0.048|
| BaA     | 0.718 | 0.460 | 0.111 |
| Chr     | 0.751 | 0.434 | 0.142 |
| BbF     | 0.727 | 0.412 | 0.041 |
| BkF     | 0.704 | 0.210 | 0.492 |
| BaP     | 0.767 | 0.124 | 0.266 |
| InP     | 0.766 | 0.079 | 0.324 |
| DahA    | 0.530 | 0.001 | 0.484 |
| BghiP   | 0.682 | 0.067 | 0.219 |
| Variance contribution rate (%) | 31.89 | 25.85 | 14.71 |
| Cumulative variance contribution rate/% | 31.89 | 57.74 | 72.45 |
that principal component 3 mainly comes from the combustion source of diesel and biomass. To sum up, PAHs in the soil of the study area mainly come from the combustion source of gasoline and diesel, oil pollution source and biomass combustion source.

3. Conclusions

(1) The average total content of PAHs in the surface soil of the region around the Qinghai Lake is 318.37 μg·kg⁻¹. The concentration of Σ₁₆PAHs in samples ranges from 169.00 to 638.94 μg·kg⁻¹, and the content of monomer PAH ranges from 0.33 to 215.17 μg·kg⁻¹. PAHs with 2–3 rings account for a highest proportion of 49.22% of the mass faction, occupying a dominant position, PAHs with 4 rings account for 31.06% while PAHs with 5–6 rings account for 19.72% of the mass fraction. Among all samples, DahA with 5 rings has a lowest relative content, while Phe with 3 rings has a highest content.

(2) The source analysis indicates that most of the sampling points are affected by vehicle exhaust and combustion of biomass and coal, while individual sampling points may also be polluted by the leakage of petrochemicals in the mining and transportation process.

(3) Ecological risk evaluation is carried out according to the toxic equivalent quantity of BaP and risk quality standard, it thus can be seen that PAHs in the soil of the study area have a lower risk, only individual areas have a toxic equivalent quantity higher than the target reference value, and the ecological risk of the soil in the study area is low. An ecological risk assessment of Bap toxicity equivalent showed that only 7.87% of the soil samples presented a slight ecological risk, and the TEQBap values of the remaining soil samples were lower than the standard reference values.

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Data availability statement

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

Author Contributions

Tianjie Shao conceived and designed the experiments; Zongyan Chen, Zhiping Xu, Yadi Zhu, Dongze Li, Lijuan Fu and Feier Wang performed the experiments; Zhongdi Zhang and Peiru Wei analyzed the data; Zhongdi Zhang was the initial contributor, Yadi Zhu participated in the later revision work. All authors have read and agreed to the published version of the manuscript.

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