Application of AHP – Entropy–TOPSIS methodology for soil heavy metal classification: Analysis of soil environment status in Jingshan as a case study

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Abstract

Given the complexity of the soil environment, the evaluation of soil pollution should consider the comprehensive weight of multiple evaluation factors to obtain highly objective and scientific conclusions. In this paper, two main ways are proposed to comprehensively analyze the degree of heavy metal pollution in the region: the combination of subjective weight (the analytic hierarchy process method) and objective weight (the entropy method) to determine the combination weight, and the use of the TOPSIS method to quantify the relative relationship between samples and the soil background values in the study area and analyze the spatial and geographical distribution of heavy metal elements in the samples. Analysis results show that the weight ranking of 31 out of 56 samples in the study area is higher than that based on the soil background value of Hubei Province, indicating that 55.36% of the samples had a comprehensive pollution degree lower than the soil background value of Hubei Province. According to the spatial distribution of heavy metal pollution, the soil pollution status in the study area is poor, and some parts are polluted by heavy metals to a certain extent.

1. Introduction

The soil environment, as a necessity for agricultural production, indirectly affects human health through the food chain and is related to human life (Xie, Peng, Wang, & Chen, 2018). Heavy metal pollution in soil has become a prominent environmental problem with the rapid development of industrialization and urbanization. In China, the area of cultivated land contaminated by Cd, As, Pb, Hg, Zn, and other heavy metals is nearly 20 million hm$^2$, accounting for approximately one-fifth of the total farmland area. Heavy metals in soil have received great attention worldwide for not only their persistent pollution to the environment but also their irreversible severe damage to the human body (Baath, 1989). Cr, Hg, As, Cu, Zn, Ni, Pb, and Cd have been rated as the priority control of pollutants by China, the European Union, the United States, and other countries as the priority in pollutants control of pollutants and are also among of the main measurement indicators for the risk assessment of agricultural soil in China. Among them, Cr, As, Cd, and other elements are assessed to have a primary carcinogenic risk (Cai, Li, Song, Gao, & Wu, 2019).

Currently, heavy metal pollution in soil is studied using various methods. Izah et al. evaluated the pollution load indices of heavy metals in soil contaminated with cassava mill effluents in a rural community in the Niger Delta region of Nigeria using the pollution load index method, considering nine pollution indices, namely, the contamination factor (CF), the degree of contamination (CD), the pollution load index (PLI), the pollution index (PI), the sum of the pollution index (SPI), the pollution index/contamination Index (PI/CI), the metal pollution Index (MPI), the average pollution index Pollution Index (API), and the Nemerow integrated pollution index (NIPI) (Izah, Bassey, & Ohimain, 2017). Tang et al. (2012) used the geoaccumulation, single-factor pollution and comprehensive pollution indices to evaluate the environmental quality of orchard soil to find the characteristics of heavy metals in the soil of spatially and vertically distributed evergreen orchards, address the causes of pollution and provide suggestions for pollution control. Alvarado Zambrano and Green-Ruiz (2019) studied the San Juan de los Planes agricultural valley using seven geochemical indices, two ecotoxicological indices, and two health risk indices including the enrichment factor (EF), the geoaccumulation index (Igeo), the CF, the CD, the modified contamination degree (mCD), the PLI, the comprehensive pollution index (Pn), the potential ecological risk factor (Er), the index (RIEc), the hazard index (HI), and the carcinogenic risk index (RI), to revise the possible ecological risks and health risks for the inhabitants due to the presence of these elements. On the basis of these index methods, several model index methods have been also introduced. Li and Han determined and analyzed the heavy metal content (i.e., Cr, Mn, Cu, Zn, As, Pb, and Fe) in the soils of different functional areas of Suzhou City through X-ray fluorescence spectrometry and the fuzzy
mathematical model (Li & Han, 2013). Delgado and Romero (2016) used a new integrated method for environmental conflict analysis in which the grey clustering method is applied to quantify qualitative information and the entropy-weight method is applied to identify the divergent criteria in a case study of a mining project in Northern Peru. In addition, many new methods have been formed from the cross-application of different disciplines in recent years, such as the single-factor contaminant index, the Nemerov multi-factor index method (Xing-Tao et al., 2010; Zhou, Chen, Pan, Zeng, & Wu, 2018), and the geostatistical (Demougeot-Renard H & Fouquet C D, 2004).

The TOPSIS method, which approximates the ideal solution method, is a multi-objective decision-making method. The principle of the TOPSIS method is to verify the evaluation result by calculating the distance between the constructed multi-index positive and negative ideal solution and the evaluated target. When TOPSIS is applied to comprehensive environmental quality evaluation, it mostly involves agricultural development (Wang et al., 2019) and water environmental quality evaluation (Lin, Shen, Zhou, & Xu, 2020), which has a low frequency in the field of soil evaluation. Urban soil pollution is evaluated through an efficient and simple algorithmic model referred to as the entropy-method-based TOPSIS model which was proposed by Liu et al. (2016). The TOPSIS method has the advantages of low information loss, high computing efficiency and wide application. During soil environmental quality evaluation, this method can be combined with reference standards, such as soil background value, to obtain the relationship between the sampling point and the soil background value and pollution between different sampling points. In this study, the heavy metal pollution in Jingshan City was evaluated using the analytic hierarchy process (AHP), entropy, and TOPSIS methods to link the harm of heavy metal pollution to crops with the biodiversity indicators of heavy metals. Meanwhile, its spatial distribution characteristics and main sources are also studied to provide a scientific basis for the ecological environmental protection of cultivated soil and heavy metal pollution prevention in Jingshan.

2. Materials And Method

2.1 Study area

The Jingshan City study area is located in the central region of Mainland China, at east diameter 112°43′–113°29′ and north latitude 30°42′–31°27′. The total study area is approximately 3500 km$^2$ (Fig. 1). Owing to the transition area between plain and low mountains, the hills are relatively large and the proportion of plain area is small. The land resources in Jingshan are especially sufficient. Agricultural land accounts for 88.14% of the total land resources, that is, approximately 294,000 ha. With outstanding natural geographical conditions and a long history of agricultural development, Jingshan City is one of the pilot cities of ecological agriculture in China and one of the important grain producing areas in Central China. The plain of Jingshan City occupies a core position in the strategy of building the Yangtze River Economic Belt and is an important agricultural foundation for realizing the rise strategy of Central China. The area of Jingshan City has abundant water flow, and the city's agricultural land is mainly distributed in slices, occupying 85% of the land in the area. Meanwhile, the city's agricultural land has many and poultry, mineral development, chemical, medical, and other industries/enterprises. Therefore, heavy metals and organic pollution is produced during agricultural production and industrial activities. The migration and diffusion of surface runoff and irrigation water cause the non-point source pollution of agricultural land, such as the non-point source pollution of heavy metal Hg in the paddy fields in Shilong Town, Yanmen Town, and Qianchang Town in the region.

2.2 Sample collection and determination
Soil sample collection was carried out in October 2020. Collected in the Jingshan City area, a total of 56 from 0 –20 cm farmland soil on the surface of soil sample. After air drying and crushing, the acid and alkaline properties of the soil samples were detected using the potentiometric method (Zvonimir et al., 2019) on the basis of the national standard of China (GB7589-87). During the measurement, an atomic fluorescence photometer was used for the Hg and As in the soil samples. For Ni, Cu, Zn, Cd, Pb and Cr, an inductively coupled plasma mass spectrometer was used.

2.3 Study method

During the application of the TOPSIS method, the importance of the accurate weighting of decision indicators is emphasized, which will have an intuitive impact on the evaluation results. The deviation from the actual situation is often caused by improper weight assignment and excessive subjectivity. Therefore, for a highly objective and accurate evaluation, this study adopted the comprehensive pollution analysis method of improved AHP, entropy weight, and TOPSIS to evaluate the heavy metal pollution of farmland soil in Jingshan City. The evaluation process is shown in Fig. 2.

The weight of the comprehensive evaluation of soil environmental quality must be clear. As a key link to the research on the environmental evaluation system, the method of right confirmation has attracted wide attention. The hierarchical analysis method (AHP) was first proposed by the scholar Saaty T. L and developed rapidly for practical use (T. Saaty, and, L., & Vargas, 1979).

Given the objectivity of the presence of heavy metals in the soil medium, the capacity and critical content of these elements change when the soil type changes. Therefore, when using the AHP method, for a highly objective and accurate judgement of the weight of the heavy metals in Jingshan agricultural soil, in the national standard “food hygiene standard” and heavy metal toxicity response index on the basis of the heavy metal concentration in Jingshan agricultural soil relative to the soil background value of Hubei Province as the third index. The greater the excess rate, the more sampling points where the element enrichment, the weight it should be given. The weight determination is divided into the following 4 steps.

Step 1. Determining the weights by AHP method.

First, Layer A is the target layer, which represents the assessment of soil pollution in a certain area. Second, Layer B is the standard layer which is divided into B1, B2, and B3, representing the Chinese food hygiene standard (GB2715-2005) limited value, the toxicity response coefficient (Hakanson, 1980), and the soil background value in Hubei Province, respectively. Finally, Layer C is defined as the evaluation factor, consisting of Hg, As, Ni, Cu, Zn, Cd, Pb, and Cr.

The matrix is divided into two levels, The first level consists of The Layer A to Layer B decision matrix, and the second level is the Layer B to Layer C decision matrix. The two levels must needs to be constructed separately. The Layer A to Layer B determination matrix is discussed in the literature (Hakanson, 1980; Y.Wang, Guo, Yi, & Chen, 2016), taking the scale shown in Table 1. The importance of the three indicators in standard Layer B is judged. Then, the determination matrix of Layer A to Layer B is obtained.
Table 1
Judgment scale and description of the Layer A to Layer B matrix

| Score | Definition (compare factor i to j) |
|-------|-----------------------------------|
| 1     | Equal                             |
| 2     | Moderately                        |
| 3     | Strongly                          |
| 4     | Very strongly                     |
| 5     | Extremely                         |

In the process of constructing the decision matrix, if the factors are extremely large, the 1–9 scale method is generally used. On this basis, some scholars (Han & Xie, 2015) have improved the AHP method and proposed the three-scale method, which has obvious advantages. To improve the accuracy of the construction decision matrix, the best transfer matrix assistance can effectively compensate for the ambiguity (Jian-Hong, Wang, Wen, & Zhao, 2018) brought by the subjective judgment of the traditional methods. Therefore, the Layer B to Layer C determination matrix is constructed using a three-scale method. First, the comparison matrix D is constructed as $D = (d_{ij})_{n \times n}$, which defines $d_{ij}$ according to the “food hygiene standard” the heavy metal toxicity coefficient, and the heavy metal soil concentration according to the OverRate of the soil background value in Hubei Province, as shown in Table 2.

Table 2
Detailed standard values for the Layer B

| Objects              | Hg  | As  | Ni  | Cu  | Zn  | Cd  | Pb  | Cr  |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Food hygiene standard limit value | 0.02 | 0.15 | 0.4 | 10  | 50  | 0.2 | 0.2 | 1   |
| Toxic response coefficient    | 40  | 10  | 5   | 5   | 1   | 30  | 5   | 2   |
| OverRate (%)          | 96.43 | 39.29 | 3.57 | 14.29 | 12.50 | 3.57 | 14.29 | 0.00 |

Decision matrix C is calculated using Eq. 3.

$$d_{ij} = \begin{cases} 2 & i > j \\ 1 & i = j \\ 0 & i < j \end{cases}$$  \hspace{1cm} (1)

$$r_i = \sum d_{ij} (n = 1.2 \ldots n)$$  \hspace{1cm} (2)

$$C_{ij} = \begin{cases} \left( \frac{(r_i - r_j)}{(r_{\text{max}} - r_{\text{min}})} \right) \times (b_m - 1) + 1 & r_i \geq r_j \\ \left( \frac{(r_j - r_i)}{(r_{\text{max}} - r_{\text{min}})} \right) \times (b_m - 1) + 1 \times r_i & r_i < r_j \end{cases}$$  \hspace{1cm} (3)

where $r_{\text{max}} = \text{Max}(r_i)$, $r_{\text{min}} = \text{Min}(r_i)$, $b_m = r_{\text{max}} / r_{\text{min}}$
The consistency ratio (CR), which is defined as the ratio of the matrix consistency and random indices, is used to describe the probability of generating random matrix judgments (Malczewski 1999). If $CR \geq 0.10$, then the decision matrix should be modified to bring CR to a satisfactory range.

$$CR = \frac{CI}{RI}$$

where RI is the average of the resulting consistency index, which depends on the index (CI) expressed as:

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$

$$\lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(C \ast W)_{i}}{n \ast w_{i}}$$

Where $\lambda_{\text{max}}$ is the largest or principal specific value of the matrix, $n$ is the order of the matrix, and $W$ is the eigenvector.

Arithmetic averaging is used to calculated weight $W_{aj}$. First, the decision matrix is normalized according to the column standard, and then summed, and finally calculated between all the elements in the resulting vector and the quotient of $n$. The specific formula is as follows:

$$W_{aj} = \frac{1}{n} \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} (i = 1, 2, 3, \ldots, n)$$

### Step 2. Entropy Method

The concept of entropy, which originated from thermodynamics, is used to measure the level of chaos of the system and has been widely adopted in multiple domains (Gao & Yang, 2009). In information theory, entropy theory expresses the degree of confusion of the information while measuring how much effective information exist (Qiao, 2004). Therefore, the weight can be determined by the entropy value.

Assuming $n$ evaluation targets and $m$ evaluation indicators, the original data matrix can be defined as $X_{n \times m}$ (Eq. 8):

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix}$$

where $x_{ij}$ is the actual measurements of the heavy metals in the sampling point;
The calculation for matrix X is standardized and the operations normalized using Eqs. 9 and 10.

\[
\begin{align*}
\text{Positive indicators:} & \quad s_{ij}^+ = \frac{x_{ij} - \min \{x_j\}}{\max \{x_j\} - \min \{x_j\}} \\
\text{Negative indicators:} & \quad x_{ij}^- = \frac{\max \{x_j\} - x_{ij}}{\max \{x_j\} - \min \{x_j\}}
\end{align*}
\]

The decision matrix is normalized as follows: 

\[
P_{ij} = \frac{x_{ij}^+}{\sum_{i=1}^{n} x_{ij}^+} \quad (10)
\]

The information entropy is calculated using Eq. 11. When \( P_{ij} = 0 \), making \( P_{ij} \ln (P_{ij}) = 0 \), \( \ln (P_{ij}) \) is meaningless.

\[
e_j = \frac{- \sum_{i=1}^{n} P_{ij} \ln P_{ij}}{\ln n}
\]

where \( e_j \) is the entropy of heavy metal elements, and \( n \) is the number of sampling points.

The entropy weight is calculated using Eq. 12:

\[
w_{bj} = \frac{(1 - e_j)}{m - \sum_{j=1}^{m} e_j}
\]

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**Step 3. Determine the weights comprehensively**

The weight obtained by the AHP and entropy weight methods is calculated by geometric means to obtain the comprehensive weight, which is expressed as

\[
w_j = \frac{w_{aj} \times w_{bj}}{\sum_{j=1}^{m} w_{aj} \times w_{bj}}
\]

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**Step 4. TOPSIS model calculation**

In solving the problem of heavy metal pollution evaluation, the original evaluation index matrix (V) of \( n \times m \) can be constructed as follows (Eq. 14):

\[
V = \begin{bmatrix}
  v_{11} & \cdots & v_{1m} \\
  \vdots & \ddots & \vdots \\
  v_{n1} & \cdots & v_{nm}
\end{bmatrix}
\]
where \( v_{ij} \) is the value of the evaluation index in the evaluation unit.

The standard evaluation matrix is realized through the data normalization process. The maximum and minimum indices are respectively calculated by Eqs. 15 and 16. The higher the concentration of heavy metals in the soil is, the worse the pollution situation is. Thus, it can be judged as the minimum indicator, and minimal heavy metal concentration is preferred. Standardized evaluation matrix \( R \) is expressed as Eq. 17.

\[
R_{ij} = \frac{v_{ij} - \min(v_{ij})}{\max(v_{ij}) - \min(v_{ij})}
\]

\[
R_{ij} = \frac{\max(v_{ij}) - v_{ij}}{\max(v_{ij}) - \min(v_{ij})}
\]

An evaluation matrix construction based on comprehensive weights.

When conducting soil pollution evaluation, to enhance the objectivity degree of the rating matrix, the comprehensive weights of the AHP and entropy weight methods are referenced to construct weighted matrix \( Y \).

\[
Y = \begin{bmatrix}
Y_{11} & \cdots & Y_{1m} \\
\vdots & \ddots & \vdots \\
Y_{n1} & \cdots & Y_{nm}
\end{bmatrix}
\]

where \( Y_{ij} = w_j^*r_{ij} \).

Determination of the positive and negative ideal solutions.

\( Y^+ \) is the most preferred scheme, which is defined as the maximum value of index \( j \) in point \( i \) in the evaluation data, namely, the positive ideal solution; \( Y^- \) is the least preferred scheme, which is defined as the minimum value of index \( j \) in the evaluation data, that is, the negative ideal solution.

\[
Y^+ = \left( Y_{1}^+, Y_{2}^+, \cdots Y_{m}^+ \right) = \left( \max\{Y_{11}, Y_{21}, \cdots, Y_{n1}\}, \max\{Y_{12}, Y_{22}, \cdots, Y_{n2}\}, \cdots, \max\{Y_{1m}, Y_{2m}, \cdots, Y_{nm}\} \right)
\]
\[
Y^{-} = \left( Y_{1}^{-}, Y_{2}^{-}, \ldots, Y_{m}^{-} \right) = \left( \min\{Y_{11}, Y_{21}, \ldots, Y_{n1}\}, \min\{Y_{12}, Y_{22}, \ldots, Y_{n2}\}, \ldots, \min\{Y_{1m}, Y_{2m}, \ldots, Y_{nm}\} \right)
\]

Calculate the distance.

Many kinds of distance calculation methods exist, but the Euclid algorithm is used. Let \(i=1,2, \ldots, n\). The distance between evaluation objects from the maximum is \(D_{i}^{+}\), where \(i=1, \ldots, n\). The distance between the evaluation objects and the maximum is \(D_{i}^{-}\), which is expressed as follows:

\[
D_{i}^{+} = \sqrt{\sum_{j=1}^{m} (Y_{j}^{+} - y_{ij})^2}
\]

\[
D_{i}^{-} = \sqrt{\sum_{j=1}^{m} (Y_{j}^{-} - y_{ij})^2}
\]

Calculation of the closeness between the participating target and the ideal solution.

Relative closeness is defined as point \(i\) of heavy metal pollution in soil near the optimum, which is generally expressed by \(S_{i}\). It is taken in 0–1. The greater the \(S_{i}\) value is, the nearer the soil pollution at point \(i\) is to the optimum. If \(S_{i} = 1\), then point \(i\) soil pollution is the lightest and optimal. When \(S_{i} = 0\), the soil pollution of point \(i\) is the worst. This study uses relative closeness to represent the quality of heavy metal pollution in the soil. According to the difference in the relative closeness value of different points, the degree of soil heavy metal pollution and determine the pros and cons of the ranking can be determined. The specific calculation formula is as follows:

\[
S_{i} = \frac{D_{i}^{-}}{D_{i}^{+} + D_{i}^{-}}
\]

3. Result And Discussion

3.1 Analysis of soil heavy metal content characteristics and spatial distribution

According to the statistical analysis results of heavy metal elements in soil in 56 samples (Table 5) and combined with the background value of the heavy metal in Hubei Province, the Cu, Pb, Ni, As, Zn, and Cr contents are less than the standard of soil risk screening value of agricultural land. Hg and Cd pollution, mainly Hg pollution, existed in
paddy fields. In the 56 samplings, 18 samplings exceeded the standard, which is approximately 32%. The pH value of the 56 samples ranged from 5.33 to 7.69, including 1 strongly acidic (pH ≤ 5.5), 20 weakly acidic (5.5 < pH ≤ 6.5), 33 neutral (6.5 < pH ≤ 7.5), and 2 alkaline (pH > 7.5) samples accounting for 1.7%, 35.8%, 58.9%, and 3.6% of the total numbers of samples, respectively. The Hg content of 17 samples (i.e., 1 strongly acidic, 7 weakly acidic, and 9 neutral samples) exceeded the standard, and the overstandard rate was 30.3%. The Cd element content in a strong acid sample exceeded the standard, which was a strong acid sample, and the exceeding rate was 1.7%.
### Table 5
Statistical analyzing results of heavy metal concentrations

| Object | pH (Sample quantity) | Concentration range /mg·kg⁻¹ | Farmland soil standard/ mg·kg⁻¹ | Soil background value in Hubei Province/ mg·kg⁻¹ |
|--------|----------------------|-------------------------------|-------------------------------|-----------------------------------------------|
| As     | pH ≤ 5.5 (Paddy field) (n = 1) | 7.27                         | 30                            | 12.3                                          |
|        | 6.5 ≥ pH ≥ 5.5 (Paddy field) (n = 8) | 8.14 – 17.2                   | 30                            |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (Paddy field) (n = 10) | 6.01 – 19.6                   | 25                            |                                               |
|        | 6.5 ≥ pH ≥ 5.5 (others) (n = 12) | 4.71 – 19.6                   | 40                            |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (others) (n = 23) | 5.3 – 19.4                    | 30                            |                                               |
|        | pH ≥ 7.5 (others) (n = 2) | 1.33 – 11.2                   | 25                            |                                               |
| Cd     | pH ≤ 5.5 (Paddy field) (n = 1) | 0.34                          | 0.3                           | 0.172                                         |
|        | 6.5 ≥ pH ≥ 5.5 (Paddy field) (n = 8) | 0.02 – 0.13                   | 0.4                           |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (Paddy field) (n = 10) | 0.04 – 0.15                   | 0.6                           |                                               |
|        | 6.5 ≥ pH ≥ 5.5 (others) (n = 12) | 0.02 – 0.29                   | 0.3                           |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (others) (n = 23) | 0 – 0.41                      | 0.3                           |                                               |
|        | pH ≥ 7.5 (others) (n = 2) | 0.09 – 0.12                   | 0.6                           |                                               |
| Cr     | pH ≤ 5.5 (Paddy field) (n = 1) | 0                             | 250                           | 86                                            |
|        | 6.5 ≥ pH ≥ 5.5 (Paddy field) (n = 8) | 0 – 23                        | 250                           |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (Paddy field) (n = 10) | 0 – 33                        | 300                           |                                               |
|        | 6.5 ≥ pH ≥ 5.5 (others) (n = 12) | 0 – 32                        | 150                           |                                               |
|        | 7.5 ≥ pH ≥ 6.5 (others) (n = 23) | 0 – 49                        | 150                           |                                               |
|        | pH ≥ 7.5 (others) (n = 2) | 13 – 16                       | 200                           |                                               |
| Cu     | pH ≤ 5.5 (Paddy field) (n = 1) | 23                            | 150                           | 30.7                                          |
|        | 6.5 ≥ pH ≥ 5.5 (Paddy field) (n = 8) | 8 – 23                        | 150                           |                                               |
| pH Range | Soil Type | Mean (SD) | n |
|----------|-----------|-----------|---|
| pH ≥ 6.5 | Paddy field (n = 10) | 7.5 | 200 |
| pH ≥ 5.5 | others (n = 12) | 6.5 | 50 |
| pH ≥ 6.5 | others (n = 23) | 7.5 | 100 |
| pH ≥ 7.5 | others (n = 2) | 29-30 | 100 |
| Hg | pH ≤ 5.5 (Paddy field) (n = 1) | 6 | 0.5 | 0.08 |
| pH ≥ 5.5 | Paddy field (n = 8) | 6.5 | 0.356-1.78 | 0.5 |
| pH ≥ 6.5 | Paddy field (n = 10) | 7.5 | 0.44-1.82 | 0.6 |
| pH ≥ 5.5 | others (n = 12) | 6.5 | 0.368-1.99 | 1.8 |
| pH ≥ 6.5 | others (n = 23) | 7.5 | 0.478-1.61 | 2.4 |
| pH ≥ 7.5 | others (n = 2) | 7.5 | 1.17-1.17 | 3.4 |
| Ni | pH ≤ 5.5 (Paddy field) (n = 1) | 6.5 | 24 | 37.3 |
| pH ≥ 5.5 | Paddy field (n = 8) | 7.5 | 6-25 | 70 |
| pH ≥ 6.5 | Paddy field (n = 10) | 6.5 | 0-32 | 100 |
| pH ≥ 5.5 | others (n = 12) | 7.5 | 3-36 | 70 |
| pH ≥ 6.5 | others (n = 23) | 6.5 | 6-39 | 100 |
| pH ≥ 7.5 | others (n = 2) | pH ≥ 7.5 | 26-30 | 190 |
| Pb | pH ≤ 5.5 (Paddy field) (n = 1) | 6.5 | 20.5 | 26.7 |
| pH ≥ 5.5 | Paddy field (n = 8) | 7.5 | 7.1-48.2 | 100 |
| pH ≥ 6.5 | Paddy field (n = 10) | 7.5 | 8.7-53.4 | 140 |
| pH ≥ 5.5 | others (n = 12) | 6.5 | 1.4-63.1 | 90 |
| pH ≥ 6.5 | others (n = 23) | 7.5 | 1.9-36.5 | 120 |
| pH ≥ 7.5 | others (n = 2) | pH ≥ 7.5 | 9.2-10.2 | 170 |
2)  

| Zn | pH ≤ 5.5 (Paddy field) (n = 1) | 56 | 200 | 83.6 |
|----|---------------------------------|----|-----|------|
|    | 6.5 ≥ pH ≤ 5.5 (Paddy field) (n = 8) | 34–58 | 250 |
|    | 7.5 ≥ pH ≤ 6.5 (Paddy field) (n = 10) | 35–111 | 200 |
|    | 6.5 ≥ pH ≤ 5.5 (others) (n = 12) | 34–77 | 200 |
|    | 7.5 ≥ pH ≤ 6.5 (others) (n = 23) | 35–118 | 250 |
|    | pH ≥ 7.5 (others) (n = 2) | 60–85 | 300 |

### 3.2 Weight results of AHP-Entropy

The CR of Layer A to Layer B is 0.0707 and that of layers B1, B2, B3 to Layer C is 0.0840, 0.0754, 0.0799. The CR of each layer is less than 0.1, indicating that the consistency test satisfies the requirements. The weight results of the AHP-entropy are summarized in Table 6.

| Indices | Hg | As | Ni | Cu | Zn | Cd | Pb | Cr |
|---------|----|----|----|----|----|----|----|----|
| $w_{aj}$ | 0.4013 | 0.2194 | 0.0526 | 0.0411 | 0.0177 | 0.1405 | 0.0996 | 0.0277 |
| $w_{bj}$ | 0.0895 | 0.2355 | 0.1814 | 0.1412 | 0.1181 | 0.0810 | 0.0807 | 0.0726 |
| $w_j$ | 0.3492 | 0.2731 | 0.0927 | 0.0565 | 0.0203 | 0.1106 | 0.0781 | 0.0195 |

### 3.4 Calculation results of TOPSIS

On the basis of original evaluation index matrix V, the comprehensive weight determined by the AHP and entropy weight methods is quoted, and then weighted standardized evaluation method Y is constructed. Subsequently, the positive and negative ideal solutions ($Y^+$ and $Y^-$), are determined according to the Eqs. 19 and 20 and. Then, Formulas 21 and 22 is substituted into weighted standardization matrix Y to obtain the proximity/deviation of heavy metal pollution at 56 points and the distance between the positive and negative ideal solutions of agricultural soil, as shown in Table 7.
Table 7
Heavy metal pollution of agricultural soil in Jingshan City is near/deviates from the positive and negative ideal solution

| Point Name | Di+  | Di-  | Point Name | Di+  | Di-  |
|------------|------|------|------------|------|------|
| 1#         | 0.16832 | 0.37234 | 30#        | 0.19659 | 0.35979 |
| 2#         | 0.16983 | 0.37214 | 31#        | 0.14408 | 0.36176 |
| 3#         | 0.26064 | 0.22118 | 32#        | 0.09152 | 0.39114 |
| 4#         | 0.27204 | 0.23213 | 33#        | 0.25211 | 0.24883 |
| 5#         | 0.23519 | 0.26203 | 34#        | 0.21161 | 0.33318 |
| 6#         | 0.16763 | 0.35565 | 35#        | 0.38183 | 0.19830 |
| 7#         | 0.12527 | 0.40595 | 36#        | 0.12792 | 0.36867 |
| 8#         | 0.13936 | 0.39550 | 37#        | 0.16532 | 0.34607 |
| 9#         | 0.15061 | 0.38264 | 38#        | 0.17967 | 0.33710 |
| 10#        | 0.25141 | 0.24349 | 39#        | 0.18332 | 0.32284 |
| 11#        | 0.21688 | 0.26893 | 40#        | 0.13627 | 0.35854 |
| 12#        | 0.17450 | 0.37447 | 41#        | 0.15565 | 0.35961 |
| 13#        | 0.09075 | 0.41024 | 42#        | 0.12177 | 0.37798 |
| 14#        | 0.10013 | 0.40841 | 43#        | 0.32517 | 0.18438 |
| 15#        | 0.11481 | 0.40482 | 44#        | 0.12067 | 0.39278 |
| 16#        | 0.15198 | 0.36563 | 45#        | 0.18005 | 0.32136 |
| 17#        | 0.29317 | 0.19985 | 46#        | 0.24860 | 0.29626 |
| 18#        | 0.23313 | 0.26250 | 47#        | 0.15540 | 0.33614 |
| 19#        | 0.27278 | 0.23448 | 48#        | 0.15919 | 0.33327 |
| 20#        | 0.18300 | 0.33907 | 49#        | 0.19451 | 0.33018 |
| 21#        | 0.20547 | 0.34089 | 50#        | 0.18136 | 0.33153 |
| 22#        | 0.12910 | 0.35570 | 51#        | 0.10923 | 0.39022 |
| 23#        | 0.23152 | 0.32610 | 52#        | 0.13290 | 0.35747 |
| 24#        | 0.24913 | 0.31448 | 53#        | 0.12635 | 0.39334 |
| 25#        | 0.17038 | 0.36758 | 54#        | 0.21228 | 0.34255 |
| 26#        | 0.31959 | 0.22933 | 55#        | 0.18671 | 0.36179 |
| 27#        | 0.16219 | 0.34429 | 56#        | 0.13536 | 0.36869 |
| 28#        | 0.16381 | 0.37629 | Background value of Hubei province | 0.19750 | 0.36964 |
| 29#        | 0.24383 | 0.35307 |
According to Formula 23 and the data in Table 7, the relative closeness of heavy metal pollution at 56 points of the agricultural soil in Jingshan City was obtained. The results are presented in Table 8.
Table 8
relative closeness of the pollution of heavy metals in agricultural soil in Jingshan City

| Point Name | Si    | comprehensive ranking | Point Name | Si    | comprehensive ranking |
|------------|-------|------------------------|------------|-------|------------------------|
| 1#         | 0.68867 | 21                     | 30#        | 0.64667 | 34                     |
| 2#         | 0.68664 | 22                     | 31#        | 0.71517 | 17                     |
| 3#         | 0.45906 | 53                     | 32#        | 0.81038 | 2                      |
| 4#         | 0.46042 | 52                     | 33#        | 0.49673 | 49                     |
| 5#         | 0.52699 | 48                     | 34#        | 0.61157 | 41                     |
| 6#         | 0.67966 | 27                     | 35#        | 0.34182 | 57                     |
| 7#         | 0.76419 | 7                      | 36#        | 0.75151 | 10                     |
| 8#         | 0.73945 | 11                     | 37#        | 0.67672 | 29                     |
| 9#         | 0.71756 | 16                     | 38#        | 0.65232 | 31                     |
| 10#        | 0.49200 | 50                     | 39#        | 0.63781 | 37                     |
| 11#        | 0.55357 | 45                     | 40#        | 0.72460 | 15                     |
| 12#        | 0.68213 | 25                     | 41#        | 0.69793 | 19                     |
| 13#        | 0.81886 | 1                      | 42#        | 0.75634 | 9                      |
| 14#        | 0.80310 | 3                      | 43#        | 0.36185 | 56                     |
| 15#        | 0.77905 | 5                      | 44#        | 0.76498 | 6                      |
| 16#        | 0.70639 | 18                     | 45#        | 0.64091 | 36                     |
| 17#        | 0.40536 | 55                     | 46#        | 0.54374 | 46                     |
| 18#        | 0.52963 | 47                     | 47#        | 0.68385 | 23                     |
| 19#        | 0.46225 | 51                     | 48#        | 0.67674 | 28                     |
| 20#        | 0.64947 | 33                     | 49#        | 0.62929 | 38                     |
| 21#        | 0.62393 | 39                     | 50#        | 0.64640 | 35                     |
| 22#        | 0.73371 | 12                     | 51#        | 0.78130 | 4                      |
| 23#        | 0.58481 | 43                     | 52#        | 0.72898 | 14                     |
| 24#        | 0.55798 | 44                     | 53#        | 0.75688 | 8                      |
| 25#        | 0.68328 | 24                     | 54#        | 0.61740 | 40                     |
| 26#        | 0.41778 | 54                     | 55#        | 0.65960 | 30                     |
| 27#        | 0.67977 | 26                     | 56#        | 0.73146 | 13                     |
| 28#        | 0.69671 | 20                     | Background value of Hubei province | 0.65176 | 32                      |
| 29#        | 0.59151 | 42                     |
3.5 Evaluation result analysis

The results in Tables 8 and 9 show that with the reduction of the relative closeness value, the smaller the weight ranking is, the more serious the pollution is. The comprehensive pollution weight ranking based on the relative closeness of each sampling point is shown in Fig. 5. The relative closeness value of sampling point 13 is the largest, which is 0.81886, and point 35 has the lowest relative closeness value of 0.34182. Taking the soil background value concentration of Hubei Province as the standard to participate in the weight ranking of the comprehensive heavy metal pollution in soil, we obtained that the relative closeness is 0.65176, ranking 32nd comprehensively, indicating that the comprehensive pollution degree of 31 sampling points out of 56 sampling points is less than the soil background value of Hubei Province, accounting for 55.36%. Geospatial analysis (Fig. 4) shows that the areas with a relatively ideal soil environmental quality in Jingshan City are mainly located in the north and the southwest. The lower points in the comprehensive ranking are mainly located in the west and southeast of Jingshan City, and few seriously polluted points are in the northwest and northeast of Jingshan City. Thus, the soil environmental quality of the agricultural land in Jingshan City is poor, and some areas are polluted to a certain extent.

4. Conclusion

In this study, the entropy weight method was adopted to weaken the influence of subjective bias on weight accuracy and effectively correct some defects of the traditional AHP. The TOPSIS method was used to calculate the positive and negative ideal solutions of each indicator and the distance value between the evaluation object and the ideal solution to obtain and sort the relative closeness values, quantify the relative relationship between the samples and the standards, and finally build the AHP-Entropy-TOPSIS model.

Eight common indexes of soil heavy metals, namely, Hg, As, Ni, Cu, Zn, Cd, Pb, and Cr, were selected as evaluation factors, and the soil background values in Hubei Province were used as the standard. The data of 56 sampling points in the study area were analyzed using the above model. The results show that the pollution weight ranking of 31 samples was higher than the soil background value in Hubei Province, indicating that the pollution status of these 31 sampling areas was relatively good.

The AcrMap software was used to analyze the spatial and geographical distribution of the heavy metal elements in the samples and their comprehensive ranking. The results show that the areas with a positive soil pollution status were mainly located in the north and southwest of the study area, while the areas with negative soil pollution status were located in the west and southeast of Jingshan City.

Declarations

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Code availability:
Author Contributions:

SL analyzed the spatial geographic characteristics of heavy metals in soil and was a major contributor in writing the manuscript.

QN analyzed and tabulated the collected data and improved the model creation.

XL proposed the creation of models and was a major contributor to field data collection.

LH directed the writing, review, editing and supervision of the manuscript.

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Tables 3 And 4

Tables 3 & 4 are not available with this version
Figures

Figure 1
Location of the study area in Jingshan City, Hubei Province, China

Figure 2
Four-step research methodology
Figure 3

Spatial distribution of soil chemical parameters including pH, Ni, Pb, Cd, Zn, Cu, As, Hg and Cr
Figure 4

Comprehensive pollution degree diagram of TOPSIS

Figure 5

Relative closeness value of sampling points determined by TOPSIS