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A health-risk assessment method for the preventive protection of metal cultural relics using improved rank correlation analysis and AHP fuzzy synthetic evaluation

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Abstract

This paper presents an innovative health-risk assessment methodology for the preventive protection of metal cultural relics in museums, which is based on the improved rank correlation analysis and AHP fuzzy synthetic evaluation (Relics—AHP—FSE). The approach combines the established ABC method for analyzing the pertinent environmental risk level. In this study, metal cultural relics are introduced as the research subjects. Based on the current scientific knowledge and requirements reported in international norms, a three-level index framework for assessing the health-risk is established in a hierarchical manner, and the quantitative indicators with typical correlations are proposed. The Relics—AHP—FSE approach is applied to the results of the 2022 temporary exhibition "Zhaizi China: Henan Xia, Shang and Zhou Dynasties civilization exhibition" of Shanghai Museum (China), a renowned institution boasting a significant collection of invaluable relics. In addition, the study accomplishes a scientific and practical health-risk assessment of relics. By utilizing online monitoring data and employing the expert judgment method, this study presents a comprehensive method for assessing the health-risk of metal cultural relics efficiently and conveniently. This cultural heritage protection method is specifically for safeguarding cultural relics exhibited in museums, developed in close collaboration with conservation scientists.

Keywords Metal cultural relics, Health-risk assessment, Preventive protection, Rank correlation analysis, Fuzzy comprehensive evaluation

Introduction

The preventive protection is the action taken to retard or prevent deterioration or damage to cultural properties by the control of environment and treatment of the structure in order to maintain them in an unchanging state as nearly as possible. It was first proposed at the international conservation conference in Rome in 1930. The initial concept is relatively simple and specifically referred to the preservation environment of the cultural relics, particularly the control factors such as temperature and humidity [1, 2]. With the further development and evolution over the course of more than 30 years, the preventive protection has permeated all the aspects of the cultural relics' protection. At the technical level, the preventive protection involves identifying the faced risk factors by

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the heritage through the information collection, the risk identification, the risk assessment and so on. This enables to grasp the decay mechanisms of the heritage, reduce and eliminate the risk factors effectively, and make the system engineering to keep the cultural relics in the safe state combining with the investigation and monitoring [3–5].

Metal cultural relics hold the unique artistic, cultural and scientific research value. However, the preservation environment contains various factors that can pose threats to relics. In addition to physical extrusion deformation, cracking, and damage, corrosion stands out as the most significant form of damage during the long-term preservation of relics. A large number of studies have demonstrated that temperature, humidity, pollutants, and certain microbial metabolisms can cause varying degrees of corrosion [1–3]. Environmental changes in the preservation can lead to the accelerated corrosion and the emergence of other diseases.

Therefore, it is necessary to conduct a health-risk assessment to grasp the health condition of cultural relics during preservation promptly. The current assessment still largely relies on the subjective experience of cultural and museum staff. Such subjective experience is associated with significant uncertainty and may lead to non-targeted preservation environments, exhibition, and transportation methods, potentially causing damage to relics.

There is the lack of the effective method for assessing the health-risk of metal relics in museums scientifically at moment. It is urgent to develop an efficient and convenient method to assess the health-risk with the help of scientific detection methods. To achieve a scientific assessment, it is crucial to select a systematic analysis method appropriate for the health-risk assessment.

The system analysis method refers to the method and tool for solving and optimizing problems in decision-making by utilizing the data and the related management science techniques and methods for research. However, there are few studies on the systematic analysis method specifically designed for health-risk assessment of metal relics in museums.

There are several excellent evaluation methods available for reference. The commonly used system analysis methods include AHP (Analytic Hierarchy Process) and fuzzy comprehensive evaluation.

The Analytic Hierarchy Process (AHP) is a subjective evaluation based on the expert experience. It utilizes Professor Saaty's basic 1–9 scale [4] to describe the importance of pairwise comparisons of factors at the same level quantitatively, thereby evaluating the scores of each factor on the same two levels and obtaining a judgment matrix.

In the applied research, the analysis by Nachiappan et al. [6] indicates that AHP is extensively adopted when the problem requires consideration of both quantitative and qualitative factors. Vaidya OS et al. [7] conduct a literature review on the application of Analytical Hierarchy Process (AHP). In 2022, Ing EB [8] proposes and validates that the AHP process can promote equity, diversity, and inclusion.

On the other hand, Zadeh [5] proposes the concept of fuzzy logic to formulate conclusions from unclear, doubtful, or imprecise information. The fuzzy comprehensive assessment model determines the degree of membership from the fuzzy relations through the composition principle of fuzzy relations based on fuzzy mathematics, so that it can make comprehensive judgments on objects affected by multiple factors.

In recent years, with the continuous improvement of relevant industry standards and research results, the metal health-risk assessment has been endowed with new ideas and technical means along with the development of modern analysis and detection technology. Multidisciplinary exchanges are also becoming more frequent, and the methods such as Analytical Hierarchy Process (AHP) and fuzzy comprehensive evaluation are being introduced into the field of heritage protection gradually, offering suitable assessment methods for further exploring the significance of data. These developments have provided a solid theoretical basis for studying and proposing health-risk assessment indicators, analysis methods, and evaluation techniques for cultural relics in museums.

The health-risk assessment model primarily employs the systematic analysis method to conduct quantitative data analysis on indicators. AHP and fuzzy comprehensive evaluation are applicable to the health-risk assessment of metal cultural relics in museums, and can perform quantitative data analysis on the assessment indicators. Combining both methods can form a comprehensive evaluation to reduce the risk of subjective artificial assumptions. Therefore, this paper draws on exemplary evaluation cases to systematically analyze evaluation indicators and calculate the total weight of these indicators by combining AHP and fuzzy comprehensive evaluation technology. By combining relevant system analysis and monitoring data, this study scientifically analyzes the degree of influence of evaluation indicators, the correlation between evaluation indicators and test results, as well as the authenticity of evaluation models. The primary objective of this research is to provide a comprehensive and practical health-risk assessment method in museums.

The method can well adapt to the preservation environment of cultural relics in museums, and provide the necessary theoretical support for the emergency protection and long-term protection.

Research aims

This paper presents a health-risk assessment method for the preventive protection of metal cultural relics with improved rank correlation analysis and AHP fuzzy synthetic evaluation, combining methodologies and criteria developed in the field of preventive protection. The innovation of the methodology lies in the expansive and explicit consideration of the effects of environment conditions on the works of art, based on the current scientific knowledge and consequent standard requirements.

The method aims to provide supports to museum authorities, in systematically defining critical issues and solutions, in order to.

- Propose a comprehensive health-risk assessment method for the preventive protection of metal cultural relics in museums.
- Establish the health-risk assessment index system and identify the environmental risk indicators.
- Determine the influencing order of the evaluation index parameters.
- Quantify the environment risk level assessment.
- Provide methods and supports for the exhibition, transportation and long-term preservation of relics in museums.

The assessment method is not intended to be exhaustive or definitive, but simply aims to serve as a reference for technicians and conservators who need the clear procedures to follow.

The construction of health-risk assessment index system for the preventive protection of metal cultural relics

Identification of health-risk assessment terms and definitions

The research and practice of risk management both domestically and internationally have established the fundamental terminology system of risk management, which has been standardized through international standards, national standards, industry standards and other forms. Therefore, this study adopts the basic terms and definitions in these standards as a reference to identify the fundamental terms required for the preventive risk management of cultural relics in museums.

In 2009, China formulated the GB/T 23694-2009 "Risk Management Terminology" standard, which includes 29 risk management terms. With reference to the ISO 31000:2009 standard, the national standard GB/T 24353-2009 "Risk Management Principles and Implementation Guidelines" was formulated. This standard primarily encompasses three aspects: risk management principles, risk management process, and risk management implementation, which is similar to the Australian AS/NZS4360:2004 standard. These common basic terms of risk management have important reference and guiding significance for the risk management of cultural relics in museums [9].

According to the description in GB/T 24353-2009 "Risk Management Principles and Implementation Guidelines" [10], the risk management process includes activities such as clarifying environmental information, risk assessment, risk response, supervision, and inspection. As shown in the Fig. 1, risk assessment comprises three steps: risk identification, risk analysis, and risk evaluation. Additionally, supervision and inspection should be integrated throughout all activities in the risk management process.

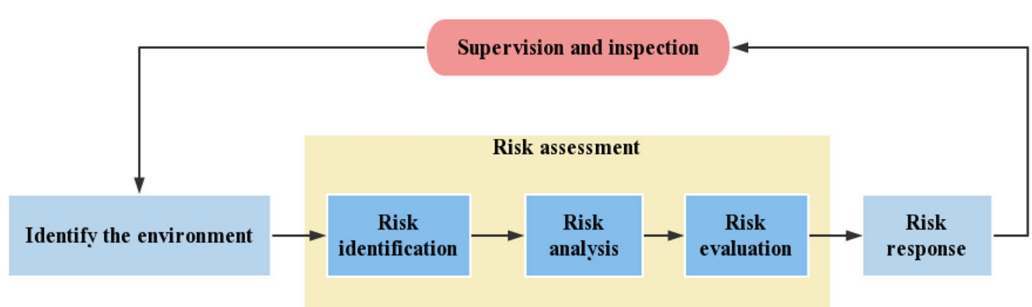

Fig. 1 The risk management process

Environmental risk indicators for preservation

Atmospheric factors influencing the corrosion of metal relics involve the reaction process of gas–liquid–solid three-phase at the interface. By studying the corrosion of metals and their alloys under the influence of different atmospheric factors, the main atmospheric factors affecting metal corrosion can be explored [11–13]. In order to identify risks systematically and methodically and minimize omission, this study adopts the environmental factors suggested by the EN 15898 (English) [14], EN 16095 (English) [15] and "Cultural Heritage Risk Management Manual" [16] published by ICCROM to identify the factors, which lead to the degradation of relics [17–20]. Based on the literature reports and experimental data summary over the years, the main environmental risk indicators and the screening reasons (degradation mechanism) are listed in Table 1.

By identifying the main environmental risk indicators, it is evident that many factors do not individually affect the corrosion of relics alone. Instead, the impact is more of a combined effect, involving various elemental compounds that collectively influence the condition of relics.

Establishing assessment index system

According to previous studies and field investigations, the Ontology of cultural relics(O), Conservation status(CS), Management using(MS), Preservation environment(PE), Preventive protection measures(PM) can affect the development of diseases significantly. Therefore, the first-level indicators should encompass these five aspects and the health-risk assessment index system is defined as:

$$\mathrm{RHR} = \Phi(\mathrm{O}, \mathrm{CS}, \mathrm{MS}, \mathrm{PE}, \mathrm{PM}) \quad (1)$$

Ontology of metal cultural relics (O)

The foundation of risk management for the preventive protection is the vulnerability of the cultural relics themselves. The vulnerability is not only related to the shape, construction process and material characteristics, but

Table 1 The main environmental risk indicators and the screening reasons (degradation mechanism)

Risk indicators	Degradation mechanism
Temperature, Relative humidity	Temperature and humidity are the primary factors influencing the corrosion of all metals Changes in temperature affect the chemical reaction rate occurring on the metal surface directly. As the temperature increases, the corrosion rate rises accordingly Similarly, humidity plays a significant role in the formation and thickness of the water film on the metal surface. As the relative humidity increases, the metal surface is more likely to absorb the water film, causing other atmospheric pollutants to become more soluble on the surface of the bronze cultural relics, thus accelerating corrosion Furthermore, these two factors interact with each other. When the absolute humidity remains constant, decreasing temperatures will lead to an increase in relative humidity. The combined effect of temperature and humidity can accelerate the formation of oxides on the surface of metal, resulting in the development of a rust layer and ultimately leading to damage to cultural relics
Lighting	Lighting plays an important role in the museum environment. Light is a kind of external energy source that can be converted into heat energy. The lighting used in showcases can affect the ambient temperature, thereby accelerating the corrosion rate of metal cultural relics At the same time, light will destroy the protective oxide layer on the surface of metal relics, causing damage to the internal matrix. Additionally, UV light causes the breakdown of ozone, which is another significant pollutant. This process leads to increased corrosion
Pollutants	In the International Cultural Heritage Conservation Science and Technology Conference, acid pollutants, specifically volatile organic acids like formic acid (HCOOH) and acetic acid (CH3COOH), were emphasized as significant pollutants in museum environments. In recent years, numerous scholars from both domestic and international backgrounds have conducted their research on the corrosion of metal cultural relics In comparison to inorganic acids, formic acid and acetic acid have lower acidity levels. However, when they combine with the water film absorbed on the metal surface, the ionized H + will reduce the pH of the liquid film, thereby accelerating corrosion. At the same time, organic acids will also accelerate the existing corrosion on the surface of relics, potentially leading to aggravated matrix corrosion Particulate matter serves as a carrier of pollutants in the atmosphere. The smaller the particle size, the greater the penetration ability. Organic acids and other substances can utilize these particles to reach the metal surface, resulting in the damage to metal culture relics Particularly, some fine particles (PM2.5) can even pass through the loose rust layer on metal surface, carrying pollutants and causing damage to the matrix. Water-soluble ions such as Cl^- and NH^{4+} can reach the surface of metal cultural relics through particles as a medium. These ions dissolve in the water film on the metal surface, forming a salt solution that accelerates the electrochemical corrosion
Biological factors	Biological factors can also play a significant role in promoting the corrosion of metal culture relics. The influence of microbial corrosion depends on several factors, including the properties of relics, the types of microorganisms, and the environmental conditions The main corrosion bacteria includes iron bacteria, thiobacillus ferrooxidans and sulfate reducing bacteria. These microorganisms utilize metal as a source of nutrition, leading to the production of organic acids and harmful gases. In addition, it involves the biological promotion in the corrosion process

also to the structural damage and material deterioration of relics. Additionally, the vulnerability is also influenced by the implementation effect of management, protection and restoration measures. The research of the preventive protection focuses on the risk caused by the preservation environment after the collection. Therefore, the model requires to be simplified.

The loss caused by the risk of cultural relics is directly related to their value, so it is necessary to evaluate the preciousness. At present, the sole measure of relics' preciousness is the classification level.

Finally, the disease status of cultural relics is also related to the risk of preventive protection [13, 21–23]. However, this study specifically focuses on the diseases related to the preservation environment during exhibition, omitting consideration of diseases carried by the cultural relics themselves, the diseases before restoration, and those unrelated to the environment. Therefore, the ontology is used as a first-level indicator, and its related indicators include the material, the degree of preciousness, and the status of diseases.

Conservation status (CS)

Preservation status is a key aspect investigated in the risk management of preventive protection for cultural relics, while the location and related use are critical content of preventive protection. Under the primary indicator of preservation status, it is divided into three secondary indicators: regional information, space and exhibition status.

Regional information refers to the climate characteristics, meteorological data, and local environmental corrosion information of the region where the museum or collection unit is located, including provinces, cities, districts, and counties.

The space is classified according to the specific environment and microenvironment in the environmental space classification, focusing on the environment surrounding relics. The state of exhibition and collection is concerned with the history and current use of relics in their specific location. The preventive protection measures vary under different usage conditions.

Management using (MS)

Regulatory use is also a considered aspect for preventive conservation. Under the first-level indicators of management and use, it is divided into three indicators: maintenance management, inspection management, and workforce.

Maintenance management involves the maintenance and disinfection of facilities to ensure their proper functioning and preservation.

Inspection management includes monitoring people's activities around cultural relics, conducting regular inspections, and generating inspection reports, among other relevant activities.

Guidance services encompass conservation and intimate exhibitions, as well as providing guidance and support to visitors and staff in the context of preventive protection measures.

Preservation environment (PE)

The risk management for the preventive protection of cultural relics in museums specifically focuses on the degradation of cultural relics caused by environmental factors. The risks caused by various natural disasters and management negligence are not included in the scope of this study for the time being.

Referring to the ten deterioration factors listed by CCI [24], the environmental factors focused on in this study include Pest, Pollutants, Light, UV and IR, Incorrect temperature, and Incorrect RH [25, 26]. Environmental factors are categorized into five groups: hot and humid environment, light environment, pollutants, biological factors, and outdoor environment.

Preventive protection measures (PM)

The preventive protection measures in the index system of risk management for the preventive protection in museums are the primary focus, which is the core of preventive protection. This study mainly focuses on the technical measures under the first-level indicators of preventive conservation measures, which are categorized into monitoring measures and control measures.

Monitoring measures encompass online monitoring of the environment, offline testing, and regular inspection and testing for cultural relics. Control measures are divided into temperature and humidity control measures, pollutant control measures, and other relevant control measures.

Based on the previous studies and investigations, this study establishes an index system shown in Fig. 2 and Table 2.

The selection and identification of assessment indicators are crucial to constructing a health-risk assessment methodology for cultural relics. The type and extent of Ontology, Conservation status, Management using and Preventive protection measures can reflect the Preservation health condition directly, and the environment where cultural relics are located can further reflect the risk level of relics.

Therefore, the health-risk assessment indicators should contain two sub-systems: health status assessment and Environment risk assessment. The indicators of health status assessment are focused representation of preservation status and conditions. They play a crucial role in assessing

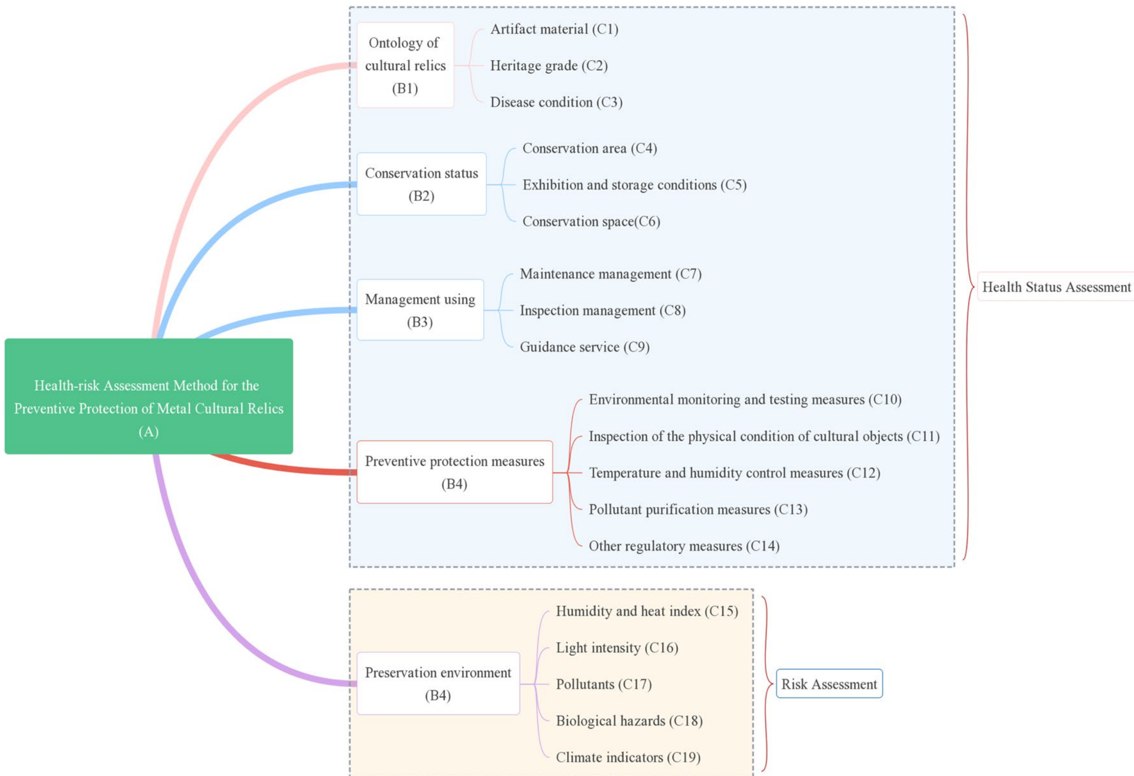

Fig. 2 The system of the metal cultural relics

the health status of relics and assisting staff in adopting targeted methods of monitoring and testing measures, maintenance management and exhibition and storage conditions, among other aspects. The environment risk assessment, which indicates the stability of the exhibition, transport and conservation, can reflect the risk expectation and help conservators to develop strategies for the long-term conservation.

Establishment of health-risk assessment method for the preventive protection of metal cultural relics

The health-risk assessment of metal cultural relics in museums involves systematically collecting the health data and evaluating the value of the data, primarily based on the ontology and environment.

The health-risk assessment includes health-risk assessment indicators, expert sort method, and an assessment model. Establishing the framework of health-risk assessment indicators first involves identifying the risk factors that affect the extraction and preservation of relics. Subsequently, an analysis is conducted to determine the extent of relevance between the main factors and the health of relics, as well as how they can be quantified [27].

According to the preservation environment and heritage conservation requirements, the health-risk assessment standards for relics are formulated based on the degree of influence of different factors on the health condition. By analyzing the state of preservation condition and health values of relics, the health levels are distinguished. Then an effective assessment of the health condition of relics is achieved through the health levels [28].

Weight determination based on improved rank correlation analysis

In this paper, the rank correlation analysis is used as an important method to determine the weight of the index. Based on the establishment of the health-risk assessment index system for the preventive protection of cultural relics, the evaluation index hierarchy is determined. The index system established in this paper is a hierarchical structure, consisting of three levels: the target level, the first-level index level, and the second-level index level. It comprises five first-level evaluation indexes and nineteen second-level evaluation indexes, with the evaluation target being the environmental risk assessment of relics.

Table 2 Health-risk assessment index system for the preventive protection of metal cultural relics

Target layer A	First-level evaluation indicators B	Second-level evaluation indicators C
Health-risk assessment index system for the metal cultural relics' environment in collection A	Ontology of cultural relics B1	Artifact material (Sensitivity of materials to damp and heat, sensitivity of materials to polluted gas, sensitivity of materials to light, sensitivity of materials to biological diseases) C1
		Heritage grade (Level 1, level 2, level 3) C2
		Disease condition(Active diseases related to conservation of the environment, Diseases associated with preservation of the environment can be induced) C3
	Conservation status B2	Conservation area (South, North, etc.) C4
		Exhibition and storage conditions (Exhibition current situation, exhibition historical information) C5
		Conservation space (Tiny environment, microenvironment) C6
	Management using B3	Maintenance management (with or without maintenance, disinfection, material selection, etc.) C7
		Inspection management (whether there is inspection, inspection frequency, records, reports, disposal plans, etc.) C8
		Guidance service (protection and the closeness of the exhibition, guidance and service) C9
	Preventive protection measures B4	Environmental monitoring and testing measures (Online monitoring, offline detection) C10
		Inspection of the physical condition of cultural objects (Inspect and observe the condition of cultural relics regularly) C11
		Temperature and humidity control measures (HVAC, debugger, moisture control material) C12
		Pollutant purification measures(Purification equipment, purification materials, collection and exhibition materials) C13
		Other regulatory measures (Light control, fumigation and disinfection, etc.) C14
	Preservation environment B5	Humidity and heat index (Temperature suitability, humidity suitability, temperature stability, humidity stability) C15
		Outdoor environment (outside temperature, humidity, rainfall, main pollutants) C16
		Biological hazards (Microorganisms, pests, and other harmful organisms) C17
		Pollutants (Acid pollutants, oxidizing pollutants, other pollutants, comprehensive assessment of pollutants) C18
		Illumination intensity (Illuminance, cumulative illuminance, UV content, other light indicators) C19

a. Determining the evaluation index hierarchy. The index system established in this paper follows a hierarchical structure, comprising three levels: the target level, the first-level index level, and the second-level index level. It contains five first-level evaluation indexes and 19 s-level evaluation indexes. The evaluation target is the preventive protection of cultural heritage collections.

b. Determining order relation. A certain number of experts are selected, and then each expert is required to determine the order relationship of each level of evaluation index, that is, rank the evaluation indexes according to the degree of importance. The basic concept is as follows: if the importance of the evaluation index V_i relative to a certain evaluation criterion is greater than the evaluation index V_j, it is recorded as $V_i > V_j$. If the evaluation index $V_1, V_2, \ldots, V_m$ has a relational expression with respect to a certain evaluation criterion

$$V'1 > V'2 \ldots > V'm \tag{2}$$

It is said that the evaluation index $V1, V2, \ldots, Vm$ establishes an sequence relationship according to "$>$". Here, V'_i represents $\{V_i\}$ the i-th evaluation index ($i = 1, 2, \ldots, m$) after the ordering relationship "$>$". For the convenience of writing, the above formula is written as

$$V1 > V2 \cdots > Vm \tag{3}$$

In the entire index system of preventive protection evaluation, it is essential to establish a sequential relationship for each second-level evaluation index and the first-level evaluation index. Therefore, each expert in this model needs to establish a sequential relationship among six evaluation indexes.

iii. Determining the importance scale and calculating the indicator weight. After determining the sequential relationship, the importance scale needs to be determined, that is, the importance ratio of the adjacent evaluation indicators in the sequential relationship list should be defined. Suppose the rational judgment of the importance scale W_{k-1}/W_k of the evaluation indexes V_i and V_{i-1} is [16–18].

$$X_K = W_{K-1}/W_K, (k = m,\ m-1, \ldots 3, 2) \tag{4}$$

Among them, W_k is the weight of the k-th index, and the value of X_k is shown in Table 3. 'm' is the number of weight indicators, when m is large, X_k can be set to 1.0.

Then W_m is

$$W_m = \left(\sum_{k=2}^{m}\prod_{i=k}^{m} x_i\right)^{-1} \tag{5}$$

Thus

$$W_{k=1} = X_k W_k (k = m, m-1, \ldots 3, 2) \tag{6}$$

Accordingly, the weight W_i of any indicator can be calculated. Subsequently, the evaluation index weights are determined based on the sequence relationship and the importance scale specified by each expert. These calculation results are combined, and the average value of the index weights is taken to obtain the comprehensive evaluation weight. The comprehensive evaluation weight vector is obtained by standardizing the calculation results.

In order to minimize the influence and provide the more objective and accurate feedback on the weighting information of the experts regarding the index system, the improved *Kendall* coordination coefficient is introduced to assess the consistency of expert weights and the *Kendall W* coordination coefficient is first used to verify the consistency of all expert weights Test [19, 20].

At first, the *Kendall's W* coefficient of concordance is employed to verify the consistency of all expert weights. The expert weight, after the consistency check, is employed as the trustworthiness information of the group weight fusion. If the overall expert weights fails in the consistency test, *Kendall Tau-b(k)* is used to test the correlation coefficient of the two experts. Experts who do not pass the *Kendall Tau-b (k)* test are required to reorder the weight of the indicators to create a new ranking. The matrix is then subjected to Kendall W test again, and this process continues until it meets the double Kendall test standard.

The process of consistency test based on *Kendall W* test and *Kendall Tau-b(K)* is as follows: for the expert ranking vector $\forall v^*_{k,j} \in v$, $v^*_{k,j}$, it is the judgement of the importance of the n indicators by the J expert, and the $v^*_{k,j}$ is arranged in sequence from small to large to form $A_{k,j}$, which constructs the ranking number vector as $A_{k,j} = (a_{k,j,1}, a_{k,j,2}, \ldots a_{k,j,n})$, $a_{k,j,l} (1 \le l \le n)$ and the order in the ranking number vector $A_{k,j}$.

Using the *Kendall* coordination coefficient form test, the expert agreement is expressed as follows:

$$kendall(W) = \frac{12\left[\sum_{k=1}^{n}\left(\sum_{j=1}^{j} a^*_{k,j,l}\right)^2 - 3j^2 n(n+1)\right]^2}{j^2\left(n^3 - n\right)} \tag{7}$$

Based on the Kendall Tau-b(K) test of the correlation coefficient of the two experts, SPSS data analysis software is used to form a multivariate sorting matrix by introducing the expert information into the data editor, and conduct a two-sided test of bivariate correlation.

Table 3 X_k assignment reference

X_k	Instructions
1.0	Index V_{k-1} is as important as V_k
1.2	Index V_{k-1} is slightly more important than V_k
1.4	Index V_{k-1} is obviously more important than V_k
1.6	Index V_{k-1} is more important than V_k
1.8	Index V_{k-1} is extremely important than V_k
1.1, 1.3, 1.5, 1.7	Intermediate situations

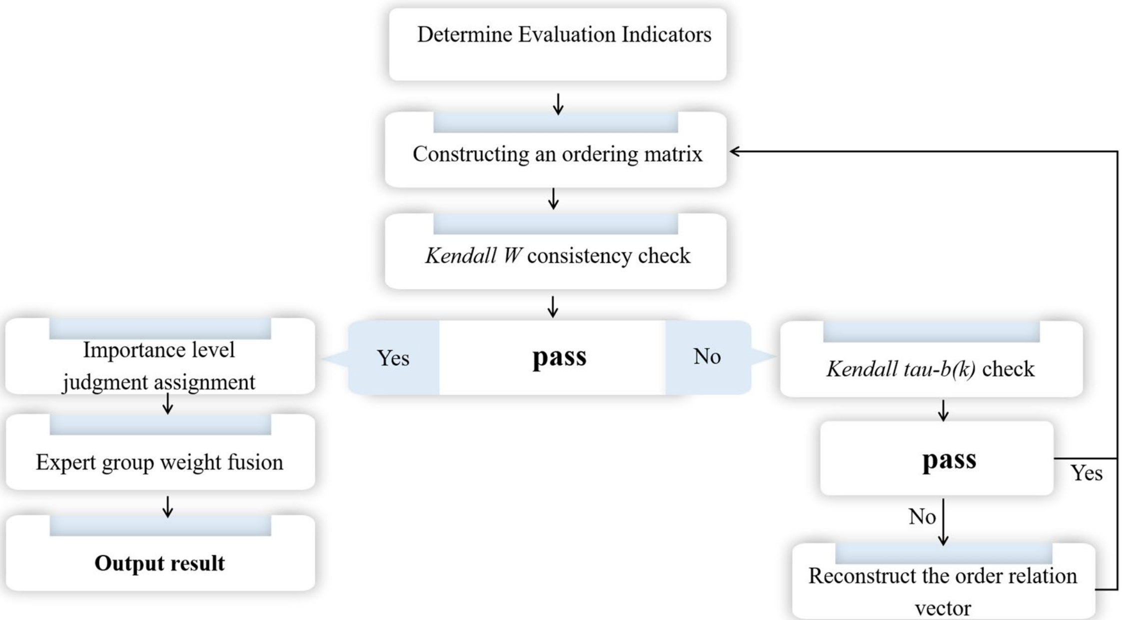

Fig. 3 The flowchart of the double Kendall consistency test

Table 4 Expert ranking in order relation method

Index	Expert 1	Expert 2	Expert 3	Expert 4
V_1	1	2	1	5
V_2	2	1	2	4
V_3	3	4	5	3
V_4	4	3	3	2
V_5	5	5	4	1

Table 5 Kendall Tau–b(K) index correlation based on SPSS

The correlation coefficient	Expert 1	Expert 2	Expert 3	Expert 4
Expert 1	1	0.6	0.6	− 1
Expert 2	0.6	1	0.6	− 0.6
Expert 3	0.6	0.6	1	− 0.6
Expert 4	− 1	− 0.6	− 0.6	1

When the confidence coefficient is greater than 0.5, the two experts are considered consistent in their ranking.

In the Kendall Tau-b (K) test, if the logarithm of concordance in the comparison between two experts is C and the logarithm of discordance is D. The total logarithm of the pairwise expert comparison is T, which is equal to n(n−1)/2, where n is the sample size. Tr refers to the number of pairs whose X value remains unchanged; Tc refers to the number of pairs whose Y value remains unchanged. The formula is expressed as follows:

$$Kendalltau - b(k) = \frac{\mathrm{C} - \mathrm{D}}{\sqrt{\mathrm{T} - \mathrm{T_r}}\sqrt{\mathrm{T} - \mathrm{T_c}}} \tag{8}$$

Based on the *Kendall* shape and *Kendall Tau-b(K)* consistency test, the weight of the sequence relation method is determined the whole process is shown in Fig. 3.

Table 6 The index weights of the results of the dual *Kendall* test

Index	V_1	V_2	V_3	V_4	V_5	S^2
Before correction	0.23	0.23	0.17	0.2	0.17	0.027
After correction	0.26	0.26	0.16	0.19	0.13	0.053

In order to verify the effectiveness of the dual Kendall test, four experts were constructed to illustrate the ranking of five indicators shown in Table 4.

From Eq. (7), we can get *Kendall (W)* = 0.3857. From checking the Kendall coordination coefficient table, we get the critical value $L = 0.5525$. Since *Kendall (W)* < *L*, it is necessary to perform *Kendall* on the two variables *Kendall Tau-b (K)* test. The index correlation obtained by SPSS is shown in Table 5.

It can be seen from Table 5 that the confidence coefficients of Expert 4 and Expert 1, Expert 2 and Expert 3 are all less than 0.5. The confidence coefficient of the pairwise comparison of other indicators is greater than 0.5, so Expert 4 needs to be re-ordered, and Kendall (W) = 1.478 > L for the reconstructed Expert 4 = (2, 1, 4, 3, 5) at this time in line with consistency. For the convenient comparison, it is supposed that the "assignment is 1.2", the index weights before and after the double Kendall test are obtained as shown in Table 6.

From the data analysis in Table 6, it can be seen that the standard deviation of the weight of indicators without double *Kendall* correction decreases due to the influence of inconsistent expert information degree, resulting in the decrease of evaluation accuracy and weakening of the weight of dominant indicators.

After the double *Kendall* test correction, the consistency and accuracy are significantly improved, and it is more in line with the objective reality.

Establishment of fuzzy synthetic evaluation model

The theory of fuzzy logic, initially proposed by Zadeh [5], enables the transformation of linguistic variables into quantitative reasoning. It serves as a powerful tool that accommodates both linguistic data (expert knowledge) and numerical data into the same fuzzy hierarchical structure.

Under the premise of considering and simplifying the basic factors of evaluation as comprehensively as possible, the evaluation results of each evaluation index are integrated into a total evaluation value using fuzzy mathematics and other relevant knowledge for reasoning and calculation. It leads to the formation of a comprehensive judgment, determining whether the reviewer has achieved the goal and to what extent, providing a clear conclusion or judgment on the level of distinction for the reviewed party's pros and cons [27, 28].

There are a lot of ambiguities and fuzzy concepts in the preventive protection of relics' health risk evaluation, and the problem of cultural relics' health-risk evaluation under the concept of preventive protection is a multi-objective decision-making problem at the same time. Therefore, the use of fuzzy comprehensive evaluation is a powerful tool to solve such problems. The specific steps are as follows:

a. Determining the evaluation index set. V = {*V1, V2, ... Vn*} is n indicators. Since each indicator is in a different position and has a different function, its weight is also different, so the evaluation result is also different.
b. Determining the comment set. The annotation set selected in this article is U = {U_1, U_2, U_3, U_4}, where U_1 is Acceptable, U_2 is Low risk, U_3 is Medium risk, U_4 is High risk.
c. Using rank correlation analysis to determine the weight of evaluation index.
d. Building evaluation matrix R. Firstly, a single-factor evaluation of the secondary indicators is conducted to determine the degree of membership of each factor for each evaluation level. Thereby, an evaluation matrix for a certain first-level index is formed, where the number of rows corresponds to the number of evaluation indexes and the number of columns corresponds to the number of evaluation levels. The whole evaluation process requires the establishment of an evaluation matrix for each first-level evaluation index, so it needs to establish 5 evaluation matrices in this study.
e. Establishing first-level comprehensive evaluation results. After the evaluation matrix of the first-level evaluation index is established, the evaluation results of the first-level index can be calculated. According to the theory of fuzzy mathematics, the result of comprehensive evaluation is

$$B = W \cdot R \tag{9}$$

In the formula: W is the index weight matrix; R is the evaluation matrix; "·" is the fuzzy operator, which can be set to take large and take small or multiplication operation. The model in this paper uses take large and take small. The evaluation result can be obtained after standardizing the calculation result.

f. Calculating the comprehensive evaluation result. After completing the first-level comprehensive evaluation, the comprehensive evaluation results of the health-risk evaluation indicators for preventive protection of cultural relics in the collection should be calculated based on the first-level evaluation indicators. At this time, the comprehensive evaluation matrix is composed of the first-level evaluation results. According to formula (9), the final compre-

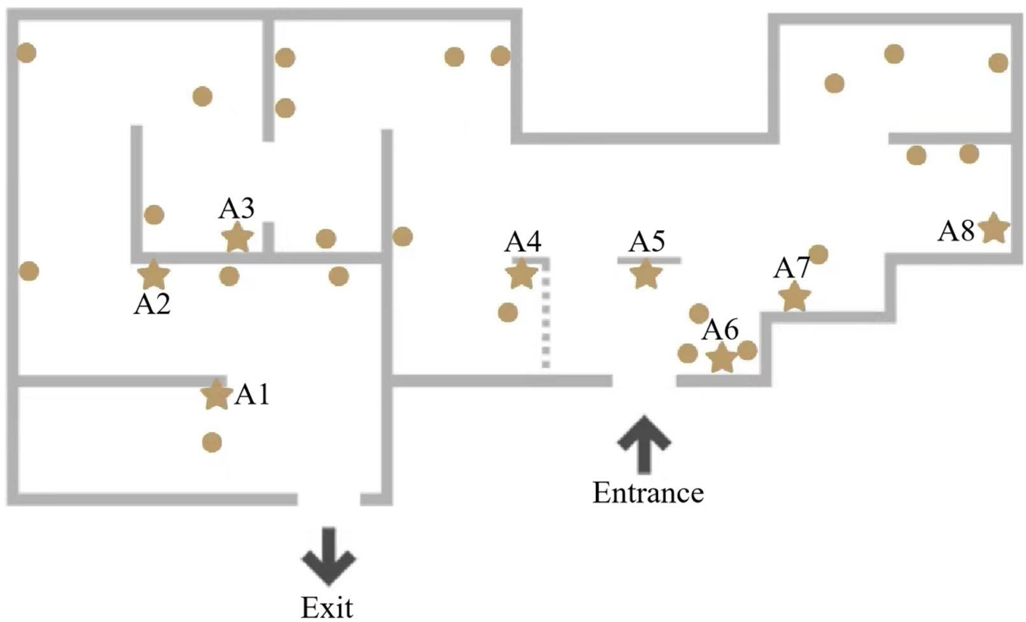

Fig. 4 Exhibition drawing of the 8 bronzes

hensive evaluation result is calculated to obtain the level of health risk evaluation for preventive protection of relics.

Materials

The proposed improved rank correlation analysis and AHP fuzzy synthetic evaluation was applied for the metal cultural relics in Shanghai Museum. A large proportion of cultural relics in Shanghai Museum are made of the metal. Some certain aged relics that carry the signature of historical and cultural importance have become susceptible to damage due to the lack of maintenance. Consequently, the health-risk assessment for the preventive protection is crucial in guiding policymakers to optimize the utilization of resources and mitigate risk.

This study is based on the 2022 temporary exhibition "Zhaizi China: Henan Xia, Shang and Zhou Dynasties civilization exhibition". Eight bronzes are selected for the study and the exhibition drawing is shown in Fig. 4, the pentagram represents the eight bronzes on display (A1-A8) and the dots represent Environmental monitoring equipment.

Methods

The research scope of the study is to identify the indicators that affect the protection of cultural relics systematically, and conducts a comprehensive assessment of the health status and environmental risks of metal cultural relics in museums through the integration of environmental monitoring data.

In this study, the health-risk assessment of relics is conducted by the methodology of Relics—AHP—FSE, based on the ABC risk level quantification method recommended by ICCROM. The detailed analysis process of the health-risk assessment is shown in Fig. 5.

The assessment index system of health-risk includes two sub-systems: Health status assessment and Environment risk assessment. The health status assessment conducts a qualitative analysis of ontology based on expert ranking and expert experience. Being able to centralize the status and conditions of preservation is critical to assessing the health of relics and can help staff take targeted monitoring and testing measures, maintenance management, and display and storage conditions. Environmental risk analysis is a quantitative analysis of cultural relics' protection environment based on monitoring data and expert experience. It shows that the stability of exhibition, transportation and preservation can reflect the risk expectation of cultural relics and help protectors formulate long-term protection strategies.

In the health-risk assessment system, a three—level index framework for assessing the health-risk is established in a hierarchical manner. In addition, the environmental risk level assessment is quantified through the changing regularity of corrosion under different environmental factors, and the quantitative indicators with typical correlations are proposed.

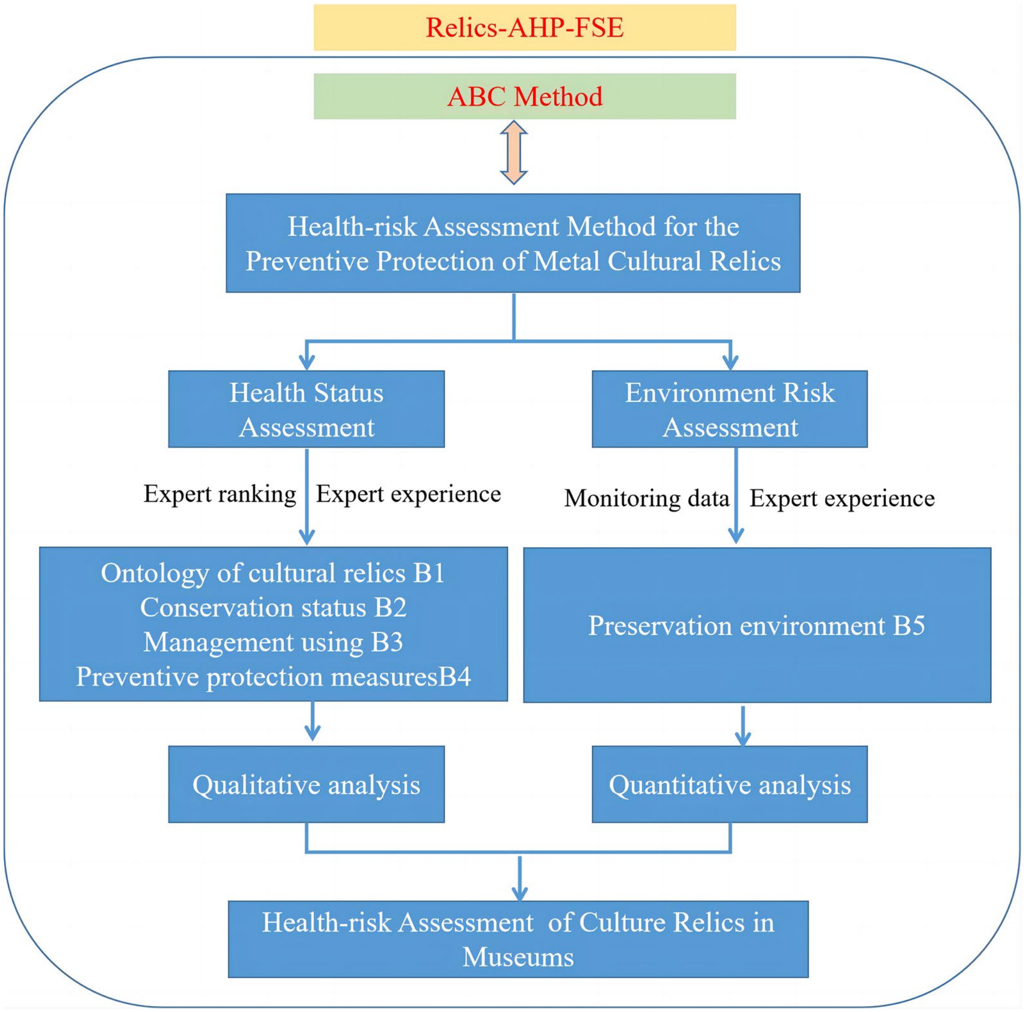

Fig. 5 Flow chart of Relics-AHP-FSE method

Environmental monitoring

Our research team has been working on the corrosion behavior of the metal cultural relics for many years, and studied the corrosion behavior of the metal materials exposed to the pollutants in the single and compound environment by the quartz crystal microbalance (QCM) reactivity monitoring method. QCMs can reflect the variable relationship between the gaseous pollutants and the metal corrosion effectively [3, 19].

The reactivity monitoring is a real-time monitoring device that utilizes metal quartz crystal microbalances (Fig. 6). The environmental reactivity monitors employing QCMs can offer real-time information on the amount of corrosion caused by the presence of gaseous pollutants. The device ensures continuous monitoring of corrosion, enabling timely preventive measures to be implemented before significant damage occurs. Appropriate reactivity and alarm levels for a particular application can be easily adjusted.

The device can operate independently as a battery-operated unit, and monitoring data can be uploaded to a PC for viewing or drawing. In this study, the online monitoring data of eight exhibits were analyzed by using QCM reactive monitoring device from environmental temperature, humidity, climate, light and pollutants. The monitoring inputs were shown in Table 7.

The expert sort method

The weight of each index was determined by adopting the method of combining expert scoring and sequence relation method, involving the selection of 10 experts.

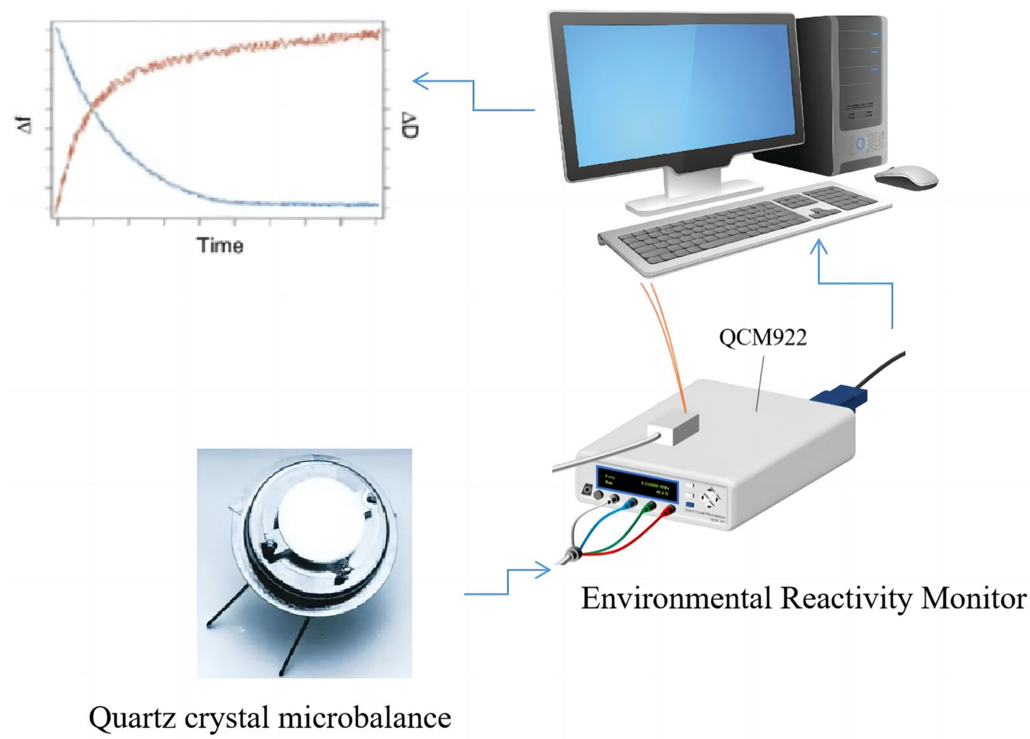

Fig. 6 Environmental Reactivity Monitor

Table 7 Environmental monitoring results

No	T(℃)			RH (%)			E(Lux)			SO_2 (μg·m^{-3})			PM(μg·m^{-3})		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
A1	23.8	21.1	22.2	52.3	51.7	52	271.7	270.7	271.4	7.8	7.2	7.4	260.3	220.4	240.5
A2	22.1	20.7	21.5	53.4	52.6	52.7	291.3	270.1	278.2	10.5	8.4	9.3	240.2	210.9	220.6
A3	23.5	21.3	22.4	52	51.6	51.9	270.9	269.5	269.9	9.7	7.3	8.5	240.3	220.1	230.6
A4	23.5	21.2	22.1	51.7	50.8	51.2	271.8	270.7	271.3	8.6	7.1	8.2	210.3	200.1	200.6
A5	25.5	24.6	25.2	68.6	59.6	63.9	266.4	262	263.8	27.4	20.3	25.1	220	210.5	219.4
A6	26.4	25.5	25.9	69.3	62.3	67.7	280.9	276.4	278.7	31.6	26.8	28.4	210.3	200.8	208.5
A7	21.5	20.1	20.9	50.1	50.1	53.4	271.2	269.8	270.6	11.5	10.7	11.3	246.3	214.2	224.2
A8	23.1	21	21.9	50.5	50.1	50.3	271.9	270.6	271.2	10.8	8.9	9.4	201.3	190.2	200.6
Exhibition hall	23.3	20.3	22.2	52.3	50.2	51.3	274.9	263.5	265.9	10.7	7.5	8.7	243.3	210.1	230.3

The experts sort the questionnaire with the small program of WeChat. According to the materials, preservation facilities, preservation equipment, management and online monitoring environment of the cultural relics in the Shanghai Museum exhibition process, the experts can sort the index information for relics requiring risk assessment by utilizing the mini-program on WeChat conveniently and efficiently.

Determination of the index weight

Taking bronze relic A1 as an example, the weights of the primary and secondary indicators are obtained based on the ranking provided by the 10 experts, as shown in the Table 8.

Taking the secondary indicators under the environmental impact indicators as an example, Index weight calculation process (Table 9) presents the sequence relationship, the importance scale of the evaluation indicators and the overall calculation results.

According to the opinions of 10 experts, the consistency test of *Kendall W* is performed firstly, and it can be obtained from formula (7) that $Kendall\ (W) = 0.9692 > L$, which is consistent with the consistency. Therefore, it is

Table 8 Weights of the indicators

Target layer A	First-level evaluation indicators B	First-level index importance ranking	Second-level evaluation indicators C	Second-level index importance ranking
Health-risk assessment index system for the metal cultural relics' environment in collection A	Ontology of cultural relics B1(0.291)	1	Artifact material C1 (0.396)	1
			Heritage grade C2 (0.291)	3
			Disease condition C3 (0.382)	2
	Conservation status B2(0.176)	3	Conservation area C4 (0.171)	3
			Exhibition and storage conditions C5 (0.269)	2
			Conservation space C6 (0.272)	1
	Management using B3(0.102)	5	Maintenance management C7 (0.122)	1
			Inspection management C8 (0.108)	2
			Guidance service C9 (0.105)	3
	Preventive protection measures B4(0.193)	2	Environmental monitoring and testing measures C10 (0.185)	3
			Inspection of the physical condition of cultural objects C11 (0.164)	4
			Temperature and humidity control measures C12 (0.191)	1
			Pollutant purification measures C13 (0.189)	2
			Other regulatory measures C14 (0.125)	5
	Preservation environment B5(0.227)	4	Humidity and heat index C15 (0.279)	1
			Outdoor environment C16 (0.195)	3
			Biological hazards C17 (0.187)	4
			Pollutants C18 (0.196)	2
			Illumination intensity C19 (0.133)	5

considered that the evaluation value of 10 experts meets the *Kendall W* test, so the *Kendall Tau-b (K)* test is not required.

According to the sequence relationship defined by 10 experts, the calculation results are combined, inferred $W_{environment} = (0.279, 0.195, 0.187, 0.196, 0.133)$. In the same way, the weights of other indicators can be calculated. The weight coefficients of nineteen secondary indicators are shown in the Table 8.

Determination of the standard value of the index

This paper focuses on the health-risk assessment of metal cultural relics for the preventive protection, the case study is the 2022 temporary exhibition "Zhaizi China: Henan Xia, Shang and Zhou Dynasties civilization

Table 9 Index weight calculation process

Expert	Rank correlation	X_2	X_3	X_4	X_5
1	$V_1 > V_3 > V_4 > V_2 > V_5$	1.4	1.0	1.2	1.3
2	$V_1 > V_4 > V_3 > V_2 > V_5$	1.5	1.3	1.0	1.5
3	$V_1 > V_2 > V_3 > V_4 > V_5$	1.3	1.2	1.0	1.2
4	$V_1 > V_2 > V_3 > V_4 > V_5$	1.2	1.0	1.2	1.3
5	$V_1 > V_4 > V_2 > V_3 > V_5$	1.4	1.2	1.0	1.3
6	$V_1 > V_3 > V_4 > V_2 > V_5$	1.4	1.2	1.3	1.4
7	$V_1 > V_3 > V_2 > V_4 > V_5$	1.3	1.0	1.0	1.3
8	$V_1 > V_2 > V_4 > V_3 > V_5$	1.3	1.2	1.1	1.2
9	$V_1 > V_4 > V_3 > V_2 > V_5$	1.4	1.1	1.3	1.3
10	$V_1 > V_3 > V_2 > V_4 > V_5$	1.3	1.0	1.2	1.2

W'_5	W'_4	W'_3	W'_2	W'_1	W_1	W_2	W_3	W_4	W_5
0.132	0.171	0.205	0.205	0.287	0.287	0.205	0.171	0.205	0.132
0.113	0.169	0.169	0.220	0.330	0.330	0.169	0.169	0.220	0.113
0.149	0.179	0.179	0.215	0.279	0.279	0.215	0.179	0.179	0.149
0.137	0.178	0.214	0.214	0.257	0.257	0.214	0.214	0.178	0.137
0.136	0.177	0.177	0.212	0.297	0.197	0.177	0.212	0.177	0.136
0.106	0.148	0.192	0.231	0.323	0.323	0.192	0.148	0.231	0.106
0.152	0.197	0.197	0.197	0.256	0.256	0.197	0.197	0.197	0.152
0.140	0.168	0.184	0.221	0.287	0.287	0.221	0.168	0.184	0.140
0.118	0.154	0.200	0.220	0.308	0.308	0.154	0.200	0.220	0.118
0.144	0.173	0.207	0.207	0.269	0.269	0.207	0.207	0.173	0.144
Average					0.279	0.195	0.187	0.196	0.133

X_i is the relative importance scale; W'_i is the evaluation index weight of the order relationship; W_i is the evaluation index weight

Table 10 Subordinate degree of secondary index under environmental impact level

Environmental impact level	Rating			
	U_1	U_2	U_3	U_4
Humidity and heat index	0.3	0.4	0.2	0.1
Light intensity	0.4	0.5	0.1	0
Pollutants	0.2	0.4	0.3	0.1
Biological hazard	0.4	0.5	0.1	0
Climate indicators	0.2	0.5	0.2	0.1

exhibition" of Shanghai Museum (China). The study investigates and studies experts from different department to evaluate various indicators, aiming to analyze and determine the safety level of preventive protection in Shanghai Museum collections.

In the index system of health-risk assessment for the preventive protection, the scoring criteria of each basic index are classified into four categories based on their sustainable development ability: "Acceptable", "Low risk", "Medium risk" and "High risk".

In order to assess the actual status of the health-risk evaluation for the preventive protection the basic indicators in the health-risk evaluation index system for environment risk assessment of cultural relics is evaluated with reference to the relevant domestic.

Establishment of membership function

When using the fuzzy comprehensive evaluation to evaluate the index system of the health-risk evaluation for the preventive protection, the evaluation matrix R must be derived firstly.

It is given that the evaluation index set V = {V_1, V_2, ..., V_n}, the comment set U = {U_1, U_2, U_3, U_4}. The r_{ij} in the evaluation matrix R is the membership degree of the index V_i corresponding to the level U_i. The model in this paper uses Zadeh ($M(\wedge, \vee)$). The evaluation result can be obtained after the calculation result is standardized.

$$b_j = \wedge_{i=1}^{n}(a_i \wedge r_{ij}) \quad (10)$$

Table 11 Comprehensive evaluation results

Comprehensive evaluation results	Acceptable	Low risk	Medium risk	High risk
B1	0.301	0.397	0.200	0.100
B2	0.270	0.369	0.271	0.090
B3	0.317	0.381	0.302	0.000
B4	0.333	0.333	0.333	0.000
A	0.314	0.314	0.245	0.126

Table 12 Health status assessment results

Comprehensive evaluation results	Final risk score	Risk level
B1	$6.788 \in [5, 7]$	Low risk
B2	$6.638 \in [5, 7]$	Low risk
B3	$7.03 \in [5, 7]$	Low risk
B4	$6.993 \in [5, 7]$	Low risk
A	$6.627 \in [5, 7]$	Low risk

Solve the membership degree of each index

After the membership function is determined, the membership degree of each index to the evaluation level is calculated according to the evaluation data of each expert, and finally the membership degree of each index level of the preventive protection health-risk evaluation is obtained.

Taking each secondary indicator under the environmental impact level of the primary indicator as an example, the results are shown in Table 10.

Comprehensive evaluation

The fuzzy comprehensive evaluation method comprehensively considers the contribution of each membership degree to the evaluation result. After obtaining the membership degree of each secondary index to the primary index, the primary evaluation result is calculated. Taking the environmental impact level indicator as an example, the grade evaluation vector is:

$$B_5 = W_5 \cdot R_5 = (0.279, 0.195, 0.187, 0.196, 0.133)\begin{bmatrix} 0.279 & 0.279 & 0.200 & 0.100 \\ 0.195 & 0.195 & 0.100 & 0.000 \\ 0.187 & 0.187 & 0.187 & 0.100 \\ 0.196 & 0.196 & 0.100 & 0.000 \\ 0.133 & 0.133 & 0.133 & 0.100 \end{bmatrix} = (0.279, 0.279, 0.200, 0.100) \tag{11}$$

After normalization, the fuzzy comprehensive evaluation result can be obtained as

$$\left(\frac{0.325}{\text{Acceptable}}, \frac{0.325}{\text{Low risk}}, \frac{0.233}{\text{Medium risk}}, \frac{0.117}{\text{High risk}}\right)$$

The calculation results show that the environmental impact degree of the "Acceptable" is 32.5%, the "Low risk" is 32.5%, the "Medium risk" is 23.3%, and the "High risk" is 11.7%. According to the principle of maximum degree of membership, the comprehensive evaluation of environmental impact is "Low risk".

The comprehensive evaluation results of each first-level index and the comprehensive evaluation results of the preventive protection in the target layer can be obtained by this method (Table 11).

Results

Health status assessment results

The final evaluation result is determined by using the scoring principle. The scoring principle is to quantify the set of reviews, that is, to use a set of appropriate numbers to represent the set of reviews, and to divide them into scientific and reasonable grades. Then, the evaluation indicators are weighted and summed to draw conclusions.

In this paper, the set of comments set is U = {High risk, Medium risk, Low risk, Acceptable}, which is quantified as U = {3, 5, 7, 9}. For the final result P, when $P \in [7, 9]$, the corresponding evaluation result is "Acceptable"; when $P \in [5, 7]$, the corresponding evaluation result is "Low risk"; when $P \in [3, 5]$, the corresponding evaluation result is "Medium risk"; when $P \in [1, 3]$, the corresponding evaluation result is "High risk". For this study

$$P = \sum_{i=1}^{4} B_i \times U_i = 0.314 \times 9 + 0.314 \times 7 + 0.245 \times 5 + 0.126 \times 3 = 6.627 \in [5, 7]$$

Therefore, the evaluation report is that the safety status of the Health status assessment of the preventive protection of relics is "Low risk" in Shanghai museum.

The result of health status assessment for each first-level index of the preventive protection in the target layer can be obtained by this method (Table 12).

According to the weight coefficient calculation of first-level evaluation indicators in Fig. 7a, the order of

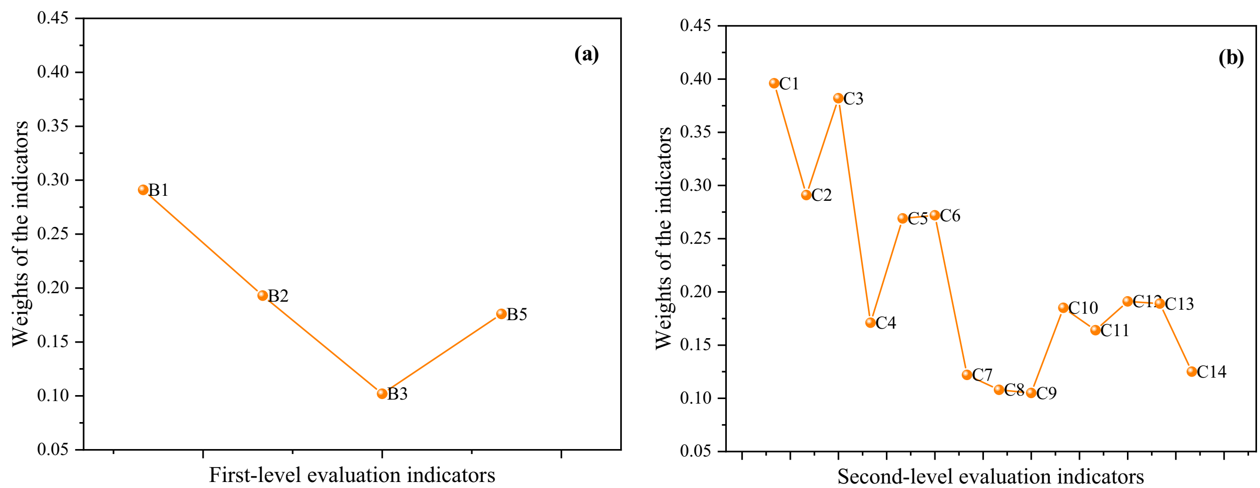

Fig. 7 The weight coefficient of the impact degree of the environmental risk assessment index for the preservation of the metal cultural relics in museums

Table 13 Risk assessment results of eight bronzes on display (A1–A8)

No	Final risk score	Risk level
A1	[5, 7]	Low risk
A2	[5, 7]	Low risk
A3	[5, 7]	Low risk
A4	[5, 7]	Low risk
A5	[3, 5]	Medium risk
A6	[3, 5]	Medium risk
A7	[5, 7]	Low risk
A8	[5, 7]	Low risk
Exhibition hall	[5, 7]	Low risk

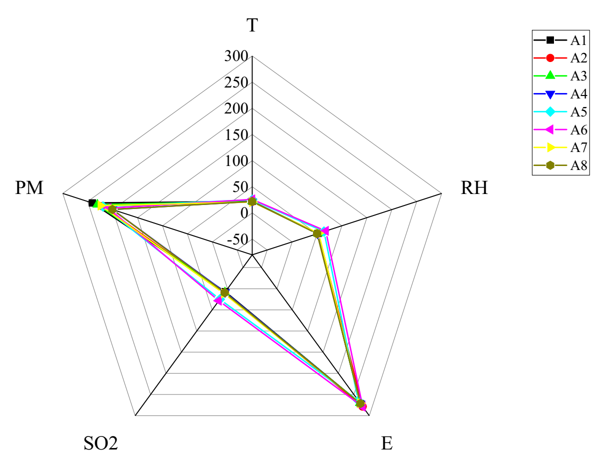

Fig. 8 Radar chart analysis results of A1–A8 bronzes preservation environment

first-level indexes affecting the health status for the preventive protection is as follows: Ontology of cultural relics (B1), Conservation status (B2), Preventive protection measures (B5) and Management using (B3). It shows that the health-status in the preventive protection is mainly affected by the cultural relics, followed by the protection of facilities, preservation conditions and management.

By calculating weight coefficient in Fig. 7b, the order of second-level evaluation indicators affecting the health status for the preventive protection is as follows: Artifact material (Cl), Disease condition (C3), Heritage grade (C2), Conservation space (C6), Exhibition and storage conditions (C5).

According to the principle of cultural relics' protection, priority should be given to the value and state of existence of cultural relics during cultural relics' preservation. The health status assessment indicators are focused representation of preservation status and conditions, which are critical to assessing the health-risk of relics and can assist staff in adopting targeted methods of monitoring and testing measures, maintenance management and exhibition and storage conditions.

Environmental risk assessment results

The environmental risk assessment can reflect the risk expectation of metal cultural relics. According to the Environmental monitoring data (Table 7), the analytical ratings of the eight exhibits and Exhibition hall are shown in Table 13

The results of the assessment show that the bronzes in Health Level “Low risk” are A1, A2, A3, A4, A7, A8 and Exhibition hall. The bronzes in Health Level “Medium risk” are A5 and A6.

Analysis of environmental risk assessment results

The radar chart can visually analyze the environmental health of the cultural relics and help the staff understand the environment affect factors. We normalized the monitoring results based on the online monitoring data in Table 7 to obtain the ’environment’ data set, which allows the five indicators to show the same correlation with the health, and facilitate graphical data analysis. The normalized data was finally utilized to generate a radar chart, as shown in Fig. 8.

It effectively shows that a smaller area of the radar chart indicates a better health condition of relics. This intuitive visualization a quick and intuitive assessment of the environmental risk assessment and aids in making informed decisions regarding the preservation strategies and preventive measures for cultural relics.

It is known that the environmental control hardware facilities affect the environment of metal cultural relics. Additionally, the most important factor influencing the environmental risk is the temperature and humidity.

As shown in Fig. 8, the showcases for A5 and A6 have relatively high Relative Humidity (RH) and SO_2 concentrations. Therefore, when exhibiting this group of cultural relics, it is essential to carefully control the humidity and SO_2 concentration in the environment and maintain suitable conditions to prevent further corrosion.

In addition, the reasonableness of the health-risk assessment method was verified by combining the comprehensive evaluation results and the results of intuitive analysis initially, which has the guiding significance.

Discussion

In order to meet the requirements of preventive protection studies for cultural relics, it is essential to establish a scientific and systematic method for assessing health-risk of cultural relics. Given the current lack of research on health-risk assessment methods for cultural relics, this study takes metal cultural relics as the research object. By combing relevant research results and national standards, this study establishes a three-level framework of health-risk assessment indicators refined layer by layer.

On this basis, this paper accomplishes a scientific and practical assessment of the health-risk. A comprehensive method for assessing the health-risk efficiently and conveniently was proposed for the first time. The method was successfully applied to the metal cultural relics in Shanghai Museum, China. In addition, this paper provides valuable insights into developing a standardized framework, which can serve as a case study for establishing a standardized framework for health-risk assessment and risk expectation.

Regarding assessment methods, the Analytic Hierarchy Process (AHP) and fuzzy synthetic assessment are widely used in various assessment cases, both inside and outside the industry. Both AHP and fuzzy synthetic assessment are equally applicable to the health-risk assessment of cultural relics in museums. The simultaneous use of these two methods allows for a combination of subjective and objective assessments, resulting in more scientific and objective results.

From the application of the proposed methodology, it is evident that the current methodology is based on metal relics, specifically bronze cultural relics, serving as an example for this study. In particular, risk assessment index system is only proposed for metal relics and may not be suitable for all types of cultural relics. Based on these considerations, future research should concentrate on detailed and exhaustive experimental studies to establish risk assessment index system for different types of cultural relics. Furthermore, future research works should focus on the application to a variety of cultural relics and transforming the proposed risk assessment methodology of metal cultural relics to a cultural relics risk assessment methodology in museums.

Although this methodology primarily focuses on the special requirement of metal cultural relics in museums, it can be extended to other environments and applicable objects easily, maintaining its basic structure. The health-risk assessment index system for the preventive protection should be established due to different cultural relics and preservation environment. On this basis, the method can assess the health-risk condition of different cultural relics scientifically and practically.

Conclusion

Relics—AHP—FSE is an innovative methodology for the health-risk assessment of cultural relics. Based on the current scientific knowledge and requirements reported in international norms, a three-level index framework for assessing the health-risk of cultural relics is established in a hierarchical manner, and the quantitative indicators with typical correlations are proposed. This paper proposed the following ideas:

(1) A comprehensive health-risk assessment method for the preventive protection of metal cultural relics in museums is proposed, which is based on the improved rank correlation analysis and AHP Fuzzy Synthetic Evaluation (Relics—AHP—FSE).
(2) The health-risk assessment index system for the preventive protection is established, and the environmental risk indicators are identified.
(3) The influencing order of the evaluation index parameters is determined according to the monitoring data.
(4) The environmental health-risk level is quantified based on the environmental risk assessment in museums.

The Relics—AHP—FSE combines quantitative analysis with qualitative analysis, so that the knowledge of operations research and fuzzy mathematics can be transferred into the comprehensive evaluation of cultural relics' preservation environment. Diverging from the traditional method of environmental monitoring system for cultural relics, this method can establish a complete comprehensive evaluation index system for the health-risk assessment of metal cultural relics in the museums. The system can calculate the adverse impact of objective factors on cultural relics risk grade evaluation through expert scores and environmental risk monitoring data. The assessment method can establish a unified environmental assessment mechanism for cultural relics of varying types, materials, and preservation statuses, which facilitate the monitoring and control of the preservation environment in museums.

The study was supported by the 2020 National Key Research and Development Program of China "Research and development demonstration of key technologies for risk prevention and control of preventive protection of cultural relics in museums". At present, the proposed approach demonstrates promising results and has already been applied to assess health risks for bronze, iron and silver cultural relics, supported by extensive data validation.

In future studies, with the accumulation of a substantial amount of data, we will further optimize the indicators, train and calibrate the assessment model, ultimately developing a scientific and complete analysis method for the health-risk assessment of metal cultural relics in museums.

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Author contributions
DL: conceptualization, methodology, software, investigation, formal analysis, writing—original draft; HZ): investigation, data curation; FX: visualization, investigation; YY: validation, visualization; LW: conceptualization, funding acquisition; LC (Corresponding Author): conceptualization, funding acquisition, resources, supervision, writing—review and editing.

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Availability of data and materials
The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests in this section.

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