Assessment of the environmental comfort of lactating sows via improved analytic hierarchy process and fuzzy comprehensive evaluation

Chong Chen[1,2], Xingqiao Liu[2*], Wenyong Duan[1], Chaoji Liu[2]

(1. *School of Electrical Engineering, Yancheng Institute of Technology, Yancheng 224051, Jiangsu, China*;
2. *School of Electrical and Information Engineering, Jiangsu University, Zhenjiang 212013, Jiangsu, China*)

Abstract: Since there are many interacting influence factors of the comfortable degree of lactating sows, a method that combines improved analytic hierarchy process (IAHP) and fuzzy comprehensive evaluation (FCE) was introduced to conduct a quantitative evaluation of the comfortable degree. Besides, an evaluation index system was established, and the weights of different indicators were determined by using IAHP method, including temperature, relative humidity, concentrations of carbon dioxide (CO_2), ammonia (NH_3), hydrogen sulfide (H_2S), and air speed. The construction method of fuzzy membership function and the calculation method of the parameters were proposed following the principle that the summation of membership degrees is equal to 1. Three basic types of membership functions (MFs), i.e., ridgemf, gaussmf, and trimf were used to build an evaluation model which fitted IAHP-FCE well. The proposed method was verified and applied based on the environmental data in different seasons obtained from a pig farm in Zhenjiang City, Jiangsu Province, China. It is demonstrated that the proposed IAHP-FCE model with various types of MFs has drawn a unique and consistent conclusion. Moreover, the IAHP-FCE model has a higher correlation coefficient of 0.874 compared with the single-factor evaluation (SFE) model. The IAHP-FCE model could be served as a beneficial strategy for the precise regulation and early warning of environmental conditions to improve sow welfare.

Keywords: lactating sow house, environmental comfort, analytic hierarchy process, fuzzy comprehensive evaluation, assessment
DOI: 10.25165/j.ijabe.20221502.6149

1   Introduction

The sow house environment is influenced by temperature, humidity, air quality, rearing density, light, and so on, which obviously has an impact on sow health, reproductive performance, and animal welfare[1,2]. The thermal environment is decided by the interaction of three physical factors, i.e., temperature, humidity, and airflow. In this study, indoor air temperature is the most important factor and an external condition to keep sow body temperature constant, which has a direct impact on the balance between heat production and dissipation[3]. The lactating sow is sensitive to a high temperature while the piglet is sensitive to a relatively low temperature[2]. Especially, high ambient temperature can adversely affect sows by increasing the body temperature and respiratory rate and decreasing the feed intake, milk production, and conception rate[4-7].

Humidity affects not only sow body heat-regulation but also the evaporation and heat dissipation from sow body surfaces. In another word, the regulation of sow body temperature is obviously affected. Humidity often shows synergistic effects along with indoor air temperature, and temperature-humidity index (THI) is therefore used for the determination of the comfort level.

Thermal comfort zone ($61 < THI \leq 65$) has a positive impact on sow reproductive performance[2]. However, high humidity can also adversely affect sows by increasing the reproduction of fungi and bacteria in sow houses, which results in sow weak immunity and respiratory infection.

Indoor air quality also plays a key role in sow health and reproductive performance. Harmful gases in sow houses originate from sow respiration and the breakdown of accumulated manure and organic matter, mainly including ammonia (NH_3), carbon dioxide (CO_2), and hydrogen sulfide (H_2S)[8]. In this study, NH_3 and H_2S were taken as toxic, corrosive, and malodorous air pollutants.

NH_3 can invade the respiratory mucosa and reduce the oxygen-carrying capacity of hemoglobin. Besides, excessive NH_3 concentration generally induces various respiratory diseases, leading to swelling in the lungs or even death. The recommended maximum NH_3 concentration for swine is 6.1 mg/m³, as specified by Iowa State University Extension Center[9], and 15.2-19.0 mg/m³ in China[10].

As a powerful nerve agent, H_2S mainly stimulates the mucous membrane. With the increase of H_2S concentration in swine houses, it becomes acutely harmful to humans and swine[11]. Low H_2S concentration can reduce immunity, and high H_2S concentration can inhibit the respiratory intensity and almost stifle sow. The recommended maximum H_2S concentration for swine is 12.1 mg/m³, as specified by Iowa State University Extension Center[9], and 12.1-15.2 mg/m³ in China[10].

Though CO_2 itself has no toxic effect, it can lead to hypoxia and CO_2 chronic poisoning when reaching a certain concentration threshold. CO_2 is related to the cleanliness of the swine house environment, and the CO_2 concentration in a dirty environment is higher than that in a clean environment. Therefore, CO_2 can be

used as an indicator for the evaluation of the health level of the swine house environment. The recommended maximum CO_2 concentration for swine is 11575.5 mg/m^3, as specified by Iowa State University Extension Center[9], and 2553.6-2946.4 mg/m^3, in China[10].

Ventilation can be used to remove the extra heat and decrease the concentration of harmful gases. However, the environmental factors are mutually coupled. The lower the CO_2 concentration is, the better the indoor air quality, but a higher air ventilation rate is required in the meantime. Especially, air speed in sow houses has chilling effects on animals, and will strongly affect sow body temperature in winter.

Sow health and reproductive performance are affected by the coupling effects of multiple environmental factors, in this case, it is quite necessary to establish a comfort evaluation model of multiple environmental factors, thereby providing decision support to the breeders for air quality management and operation optimization.

The methods for determining the environmental index weight include Delphi, analytic hierarchy process (AHP), principal component analysis (PCA), entropy weight and fuzzy group decision-making, and so on. However, each of them has its own advantage, disadvantage, and application scope. Among them, AHP is a multi-criteria decision-making method, which can be used to analyze the correlation between various indicators, and construct a judgment matrix to determine the weights among different levels[12]. Several scholars have studied AHP, and proposed improved methods. In addition, researchers have studied many algorithms to establish comfort evaluation models, such as the fuzzy comprehensive evaluation (FCE) model[13,14], the grey model[15], the principal component analysis (PCA) model[16], and the neural network model[17]. Each environmental factor is a definite value, while its description of the comfort level is a vague concept. The environmental comfort of lactating sows is difficult to be quantified. The fuzzy comprehensive evaluation model can transform qualitative evaluation into quantitative evaluation by using fuzzy set theory. Thus, the problems that the descriptions are imprecise, vague, and uncertain can be solved.

In particular, the key is to judge the attribute degree of each environmental factor by using membership degree when solving ambiguous problems in the comfort evaluation of swine house environment with fuzzy mathematics. Indeed, there are numerous different types of membership functions. Among them, the most commonly used functions in practice are normal, ridge-shape, triangular, trapezoid, etc.[18] However, there is no established criterion for the selection of the type of membership function. Moreover, the existing research only considered five influencing factors, including temperature, relative humidity, NH_3, CO_2, and H_2S when evaluating the environmental comfort. In this study, air speed was also taken as an evaluation indicator; and the coupling effects of the environmental factors, such as temperature, humidity, and air speed were considered to be able to effectively reflect the true condition with respect to the animal's response. In addition, the existing FCE method failed to analyze the influence of various membership functions on the assessment results. Due to the absence of criterion for the selection of membership function, the construction method of fuzzy membership function was proposed to provide a theoretical base for selecting membership function. To solve the problem that the environmental comfort of lactating sows is difficult to quantify, an evaluation model that integrated the improved analytic hierarchy process (IAHP) and fuzzy comprehensive

evaluation (FCE) was developed[19-21]. Furthermore, to provide decision support to environmental control in intensive livestock production, the impact of different types of membership functions on evaluation results was also investigated[22].

2　Materials and methods

2.1　Data preparation for the evaluation model development
2.1.1　Overview of the sow house

The breeding base of a pig farm selected for this study was located in Zhenjiang City, Jiangsu Province, China, with a humid climate and four distinctive seasons. In summer, it is characterized by high temperature coupled with highly humid air. The ventilation fan units and water curtains were generally employed for active cooling. The pig farm occupies an area of about 500 hm^2, and the sow house is about 50 m long, 10 m wide, and 5 m high with 36 pens in three rows. The sow building is ventilated with four ventilation fan units in the south and north end-walls. The four belt-driven exhaust fans are identical and controlled based on the indoor temperature. In addition, four water curtains of 3.0 m long and 1.6 m high on the east and west sidewalls are open during summer, which allowed additional fresh air to enter the sow house and exhaust from south and north end-walls.

2.1.2　Sow house environmental monitoring system

An indoor air quality monitoring system based on the Internet of Things (IoT) was developed, and the structure of the real-time monitoring system is shown in Figure 1. The system consists of an agricultural weather station near the sow house, several indoor air quality measuring instruments, multiple Lora communication modules, a GPRS-DTU communication module, and a remote server. A weather station is equipped with sensors for measuring air temperature, relative humidity, wind speed, wind direction, atmospheric pressure, and illumination. The main parameters of the weather station are listed in Table 1. In addition, indoor air quality measuring instrument was equipped with sensors for measuring air temperature, relative humidity, concentrations of NH_3, CO_2, H_2S, and air speed. The main parameters of sensors are listed in Table 2. Moreover, Figure 2 illustrates the deployment of sensor nodes in sow house, and the measuring height of the sensors is 1.0 m, which is also the sow height. In this study, the real-time monitoring system sampled environmental data in sow house every 10 min.
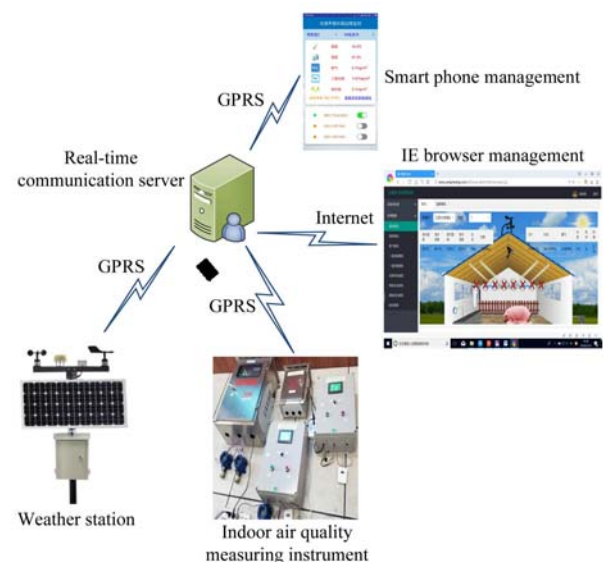

Figure 1　Structure of the real-time air quality monitoring system

Table 1   Main parameters of a weather station

Sensor	Model	Effective measurement range	Accuracy	Manufacturer
Air temperature	XF402S	−20°C-60°C	±0.3°C	
Air humidity		0-100% RH	3% RH	
Wind speed		0-30 m/s	±(0.3+0.03v) m/s	Huakong Xingye Technology Development Co., Ltd.
Wind direction		0-360°	±3°	
Illumination		0-20 klx	±5%	
Atmospheric pressure		0-120 kPa	±250 Pa	

Note: RH: Relative Humidity; v in (0.3+0.03v) m/s means the actual velocity of wind.

Table 2   Main parameters of sensors

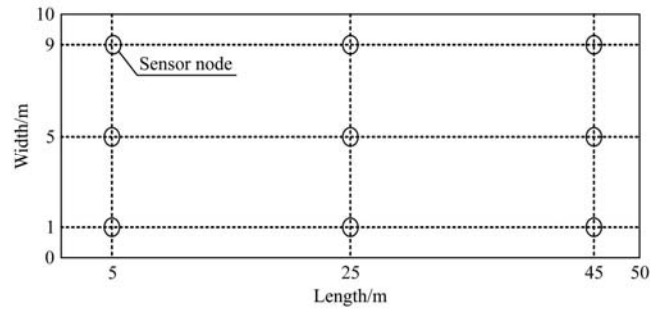| Sensor	Model	Measurement range	Accuracy	Manufacturer
Temperature and humidity sensor	AW1485B	Temperature: −20°C-60°C Relative humidity: 0-99.9%	Temperature: ±0.3°C Relative humidity: ±2%	Aosong Co., Ltd.
Gas sensor	AP-G	CO_2: 0-19642.9 mg·m^{-3} NH_3: 0-75.9 mg·m^{-3} H_2S: 0-75.9 mg·m^{-3}	≤±2%FS	Empaer Co., Ltd.
Air speed sensor	JT1402	0.05-5.00 m/s	±(0.3 m/s+2% of reading)	Jantytech

Note: FS: Full Scale.

Figure 2   Deployment schematic of sensor nodes in sow house

Environmental data on two typical days in different seasons, i.e., March 24 and July 10, 2018, were selected for the development and validation of a comfortable level evaluation model for lactating sow, as shown in Figure 3.   The two typical days represented cold and hot weather conditions, respectively.   Due to the harsh environment, the sampling data could be easily affected by various factors, such as dust, bad weather, and human interference.   To ensure the authenticity and effectiveness of environmental data, the abnormal data were eliminated by the Grubbs criterion, and the normal distribution test of the measured data was conducted in this study[23].
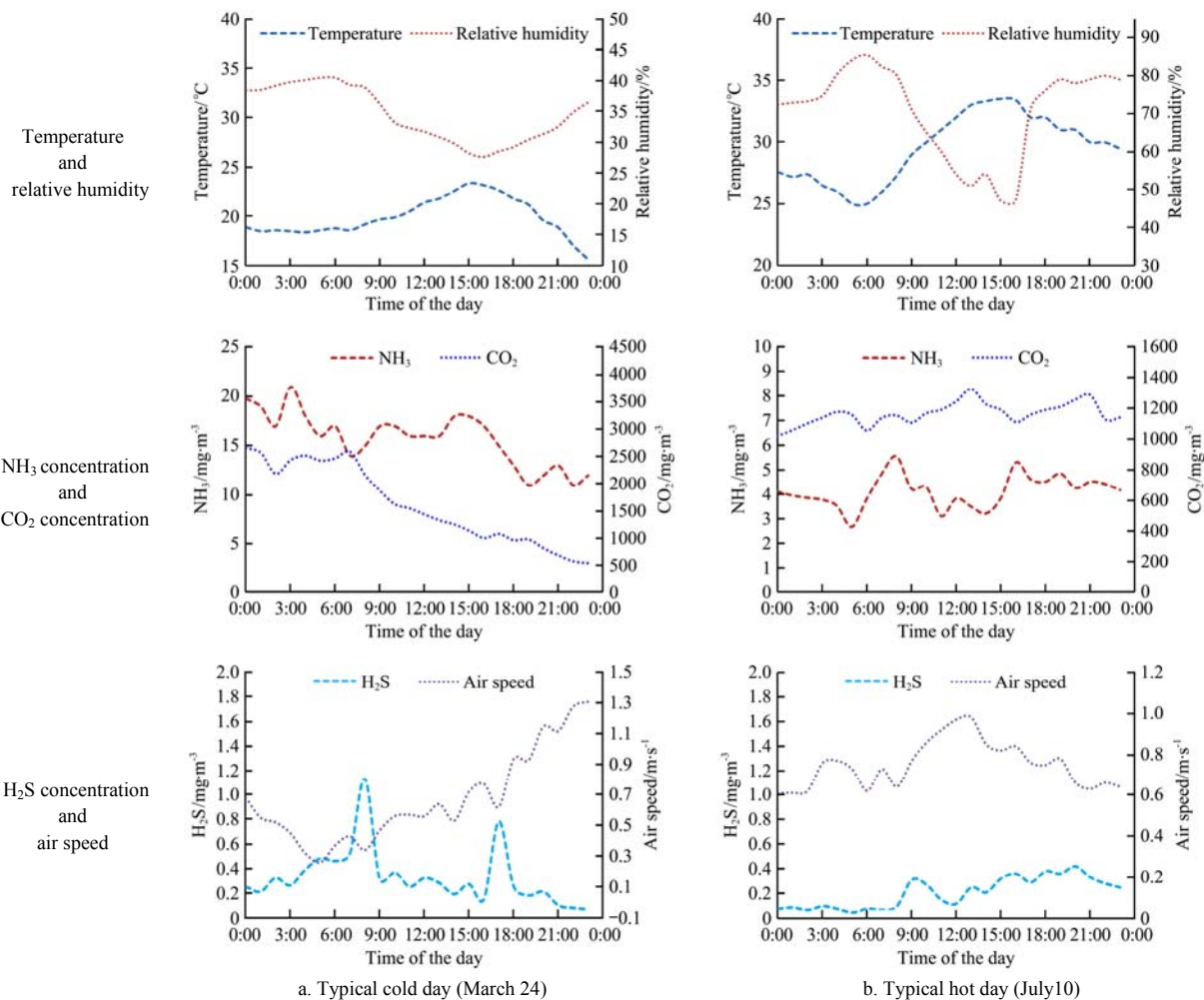

a. Typical cold day (March 24)   b. Typical hot day (July10)

Figure 3   Environmental data for model development and validation on the typical cold (March 24) and hot (July 10) days in sow house

2.2   Determination of evaluation index system

Due to the strong impacts on health and productivity of sow, temperature, relative humidity, concentrations of NH_3, CO_2, H_2S, and air speed were employed as evaluation indicators for the comfort level of lactating sow[13,14].   In this study, the comfort levels were expressed as three grades of III, II, and I, which represent "Comfortable", "Medium" and "Poor", respectively. The comfortable range of indoor environmental parameters of lactating sows were obtained according to available national standards and scientific knowledge[10,14,24].   The temperature

ranging from 18°C-22°C and the relative humidity ranging from 60%-70% were regarded as comfortable.   In addition, the comfortable concentrations of NH_3, CO_2, and H_2S were not more than 2 mg/m^3, 1100 mg/m^3, and 1 mg/m^3, respectively.   The comfortable air speed was 0.4 m/s in summer and not more than 0.05 m/s in winter.   In this way, three grades of the environmental evaluation index system were established, as listed in Table 3.

Table 3   Environment comfort evaluation index system for the lactating sow house

Factor set (*I*)	Comment set (*J*)		
	III	II	I
Temperature/°C	18-22	16-18 or 22-27	<16 or >27
Humidity/%	60-70	50-60 or 70-80	<50 or >80
$NH_3/mg \cdot m^{-3}$	0-2	2-10	>10
$CO_2/mg \cdot m^{-3}$	0-1100	1100-1300	>1300
$H_2S/mg \cdot m^{-3}$	0-1	1-2	>2
Air speed in winter/$m \cdot s^{-1}$	0-0.05	0.05-0.15	>0.15
Air speed in summer/$m \cdot s^{-1}$	0.4	0.2-0.4 or 0.4-0.6	<0.2 or >0.6

Note: "III" represents comfortable, "II" represents medium, and "I" represents poor.

2.3   Utilization of IAHP to determine the weighting vector

Due to the difference in terms of the importance of each indicator, the corresponding weights should be assigned.   The IAHP was employed to determine the weighting vector of the six influencing factors.   In this study, the environmental parameters were within the normal range.   However, it was worth noting that, although other indicators were within the range of "Comfortable", one indicator exceeded the maximum level, resulting in a fatal hazard, therefore the final comfortable level was directly evaluated as "Poor".

1) Construction of the hierarchical structure

The hierarchical structure model was established according to the comfort level evaluation indicators for the lactating sow house environment.   The evaluation index was divided into three levels, destination layer, criterion layer, and scheme layer (Figure 4).
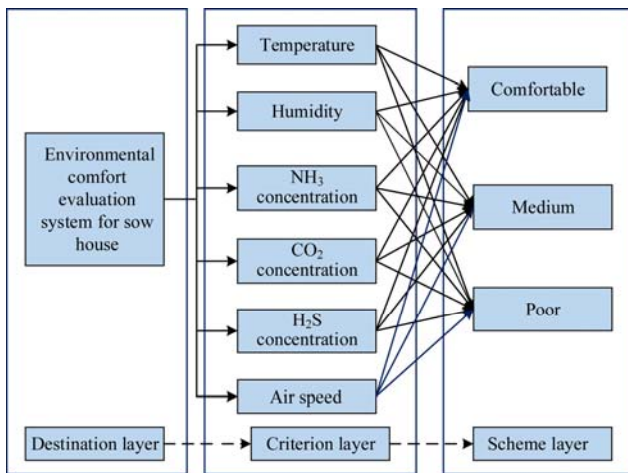

Figure 4   Environmental comfort evaluation index system for lactating sow house

The destination layer refers to the overall objective to be realized.   This study focused on the environmental comfort evaluation of lactating sows.

The criterion layer refers to the influencing factors to be considered.   This study was about the environmental parameters of temperature, relative humidity, concentrations of NH_3, CO_2, H_2S, and air speed.

The scheme layer refers to the evaluation results to be obtained.   This paper was based on the evaluation grades.

2) Establishment of the optimal matrix

The hierarchical relations of individual evaluation factors are in the form of a judgement matrix.   In this study, the importance of comfort evaluation factors in descending order was the temperature (*T*), humidity (*H*), air speed (*W*), CO_2 (*C*), NH_3 (*N*), and H_2S (*S*) according to the practical experiences and related research results[25,26].   To establish that matrix, evaluation factors at the same level are compared, and experts assess the importance of these factors by using Saaty's 9-point scale, as listed in Table 4, to form a judgement matrix *K*.

Table 4   Definitions of Satty's 9-point scale grades

Value	Definition
1	Factors *i* and *j* have the same degree of importance
3	The importance of factor *i* is slightly higher than that of factor *j*
5	The importance of factor *i* is significantly higher than that of factor *j*
7	The importance of factor *i* is much higher than that of factor *j*
9	The importance of factor *i* is extremely higher than that of factor *j*
2,4,6,8	Median value between the two adjacent values

In this study, the six factors of *T*, *H*, *N*, *C*, *S*, and *W* were compared with each other.   The method was as follows:

Suppose the six factors to be compared were $Y=\{y_1, y_2, y_3, …, y_6\}$, select two factors randomly at each time, and make six comparisons to construct the judgment matrix *G*:

$$G=(g_{ij})_{6\times6} \quad (i=1, 2, 3, 4, 5, 6, j=1, 2, 3, 4, 5, 6) \quad (1)$$

where, g_{ij} refers to the comparison result between y_i and y_j.

The values of g_{ij} were expressed by using Saaty's 9-point scale method and were calculated by Equation (2).

$$g_{ij}>0, g_{ij}=1/g_{ij} (i\neq j), g_{ii}=1 (i=j) \quad (2)$$

Therefore, an importance judgement matrix *G* of the environmental comfort was constructed as Equation (3).

$$G = \begin{array}{c} \\ T \\ H \\ N \\ C \\ S \\ W \end{array} \begin{array}{cccccc} T & H & N & C & S & W \\ \begin{bmatrix} 1 & 3 & 5 & 4 & 5 & 2 \\ \frac{1}{3} & 1 & 3 & 2 & 3 & 2 \\ \frac{1}{5} & \frac{1}{3} & 1 & \frac{1}{3} & 2 & \frac{1}{2} \\ \frac{1}{4} & \frac{1}{2} & 3 & 1 & 2 & \frac{1}{3} \\ \frac{1}{5} & \frac{1}{3} & \frac{1}{2} & \frac{1}{2} & 1 & \frac{1}{3} \\ \frac{1}{2} & \frac{1}{2} & 2 & 3 & 3 & 1 \end{bmatrix} \end{array} \quad (3)$$

Based on Equations (4)-(6), an indirect judgment matrix *D* was established as Equation (7).

$$D_{ij} = \begin{cases} \frac{r_i - r_j}{r_{max} - r_{min}}(q_m -1)+1 & r_i - r_j \geq 0 \\ 1 / \left[\frac{r_j - r_i}{r_{max} - r_{min}}(q_m -1)+1 \right] & r_i - r_j < 0 \end{cases} \quad (4)$$

$$r_i = \sum_{j=1}^{6} g_{ij} \quad (i=1,2,3,4,6) \quad (5)$$

$$q_m = \frac{r_{max}}{r_{min}} \quad (6)$$

where, r_{max} and r_{min} represent the maximum and minimum value of r_i, respectively.

$$D = \begin{bmatrix} 1.0000 & 4.0233 & 6.4535 & 5.5058 & 6.9767 & 4.4884 \\ 0.2486 & 1.0000 & 3.4302 & 2.4826 & 3.9535 & 1.4651 \\ 0.1550 & 0.2915 & 1.0000 & 0.5134 & 1.5233 & 0.3373 \\ 0.1816 & 0.4028 & 1.9477 & 1.0000 & 2.4709 & 0.4957 \\ 0.1433 & 0.2529 & 0.6565 & 0.4047 & 1.0000 & 0.2867 \\ 0.2228 & 0.6825 & 2.9651 & 2.0174 & 3.4884 & 1.0000 \end{bmatrix} \quad (7)$$

An indirect judgment matrix D was transformed into an antisymmetric matrix F (Equation (8)). After that, an optimization matrix P was established as Equation (9). In this way, the consistency requirements could be met.

$$F_{ij} = \lg(d_{ij})(i, j = 1,2,3,4,5,6) \qquad (8)$$

$$P_{ij} = 10^{\frac{1}{n}\sum_{k=1}^{n}(f_{ik}-f_{jk})} (i, j = 1,2,3,4,5,6) \qquad (9)$$

Based on Equations (8) and (9), the final optimization matrix P was established as Equation (10). As the matrix P met consistency requirements, no consistency test was necessary.

$$P = \begin{bmatrix} 1.0000 & 3.2545 & 13.0307 & 7.6176 & 17.4568 & 4.2647 \\ 0.3073 & 1.0000 & 4.0039 & 2.3406 & 5.3639 & 1.3104 \\ 0.0767 & 0.2498 & 1.0000 & 0.5846 & 1.3397 & 0.3273 \\ 0.1313 & 0.4272 & 1.7106 & 1.0000 & 2.2917 & 0.5598 \\ 0.0573 & 0.1864 & 0.7465 & 0.4364 & 1.0000 & 0.2443 \\ 0.2345 & 0.7631 & 3.0555 & 1.7862 & 4.0933 & 1.0000 \end{bmatrix} \quad (10)$$

Finally, the maximum eigenvalue $\lambda_{max}=6.0000$ of the matrix P was calculated, and the corresponding eigenvector was obtained and normalized by Equation (11). Figure 5 illustrates the weight coefficients of six evaluation factors.

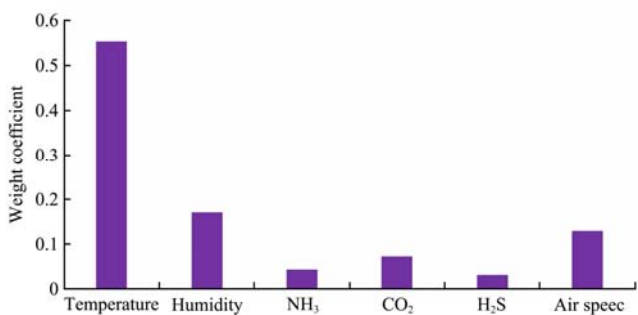$$\omega=[0.5534_T, 0.1700_H, 0.0425_N, 0.0726_C, 0.0317_S, 0.1298_W] \quad (11)$$

Figure 5   Weight coefficients of the evaluation factors

2.4   Construction method of fuzzy membership function

The description of the environmental comfort of lactating sows is not a definite value, but a fuzzy concept within a certain range. Fuzzy set theory is suitable to express fuzzy and uncertain concepts. In this study, the construction of membership functions (MFs) follows the vaguest and clearest principles[27]. The vaguest point is at the end of the interval, and the membership degree is equal to 0.5; on the other hand, the clearest point is at the midpoint of the interval, and the membership degree is equal to 1. In this study, the summation of the membership degrees of each point is equal to 1. The construction method of fuzzy membership function was proposed by combining wide and narrow functions.

Suppose the membership function is $\mu(x)$, the evaluation results are divided into k grades. As can be seen from Figure 6, the intervals of the first and the last grade employ a wide domain model.
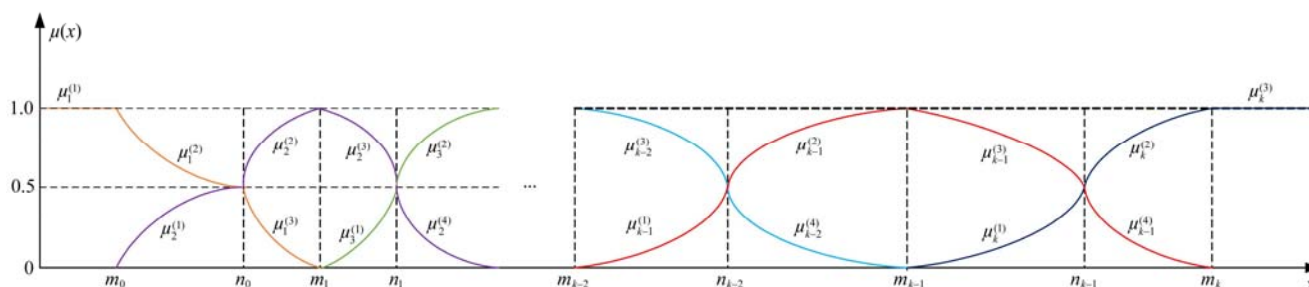
However, the intervals of other grades use a narrow domain model.

The interval of the first grade is $[0, n_0]$. In the subinterval of $[0, m_0]$, let $\mu_1^{(1)}=1$. In the subinterval of $[m_0=n_0/2, n_0]$, according to $\mu(m_0)=1$ and $\mu(n_0)=0.5$, the coefficient of $\mu(x)$ can be determined, moreover, $\mu_2^{(2)}$ can also be determined. Meanwhile, $\mu_2^{(2)}+\mu_1^{(3)}=1$, then $\mu_1^{(3)}=1-\mu_2^{(2)}$.

The interval of the last grade is $[n_{k-1}, +\infty)$. In this study, $m_k=n_{k-1}+0.5n_{k-1}$ is selected as a midpoint of the interval. When $x>m_k$, the wide membership function is adopted, and let $\mu_k^{(3)}=1$. In the subinterval of $[n_{k-1}, m_k]$, according to $\mu(n_{k-1})=0.5$ and $\mu(m_k)=1$, the coefficient of $\mu(x)$ can be determined, and $\mu_k^{(2)}$ can also be obtained.

The construction of membership functions in the intervals of other grades involves the front and back adjacent intervals. Taking the interval of $k-1$ grade $[n_{k-2}, n_{k-1}]$ for example, the construction process is as below:

1) At the intervals of $[0, m_{k-2})\cup(m_k, +\infty)$, the membership degree is 0, that is, $\mu(x)=0$;

2) At the interval of $[m_{k-2}, n_{k-2}]$, $\mu_{k-2}^{(3)}$ can be obtained according to $\mu(m_{k-2})=1$ and $\mu(n_{k-2})=0.5$. Combining the principle that the summation of membership degrees is equal to 1, $\mu_{k-1}^{(1)}=1-\mu_{k-2}^{(3)}$;

3) At the intervals of $[n_{k-2}, m_{k-1})\cup[m_{k-1}, n_{k-1})$, the specific forms of $\mu_{k-1}^{(2)}$ and $\mu_{k-1}^{(3)}$ can be obtained according to $\mu(m_{k-1})=1$ and $\mu(n_{k-2})=\mu(n_{k-1})=0.5$.

4) At the interval of $[n_{k-1}, m_k]$, based on $\mu(n_{k-1})=0.5$ and $\mu(m_k)=1$, $\mu_k^{(2)}$ can be obtained. Combining the principle that the summation of membership degrees is equal to 1, $\mu_{k-1}^{(4)}=1-\mu_k^{(2)}$.
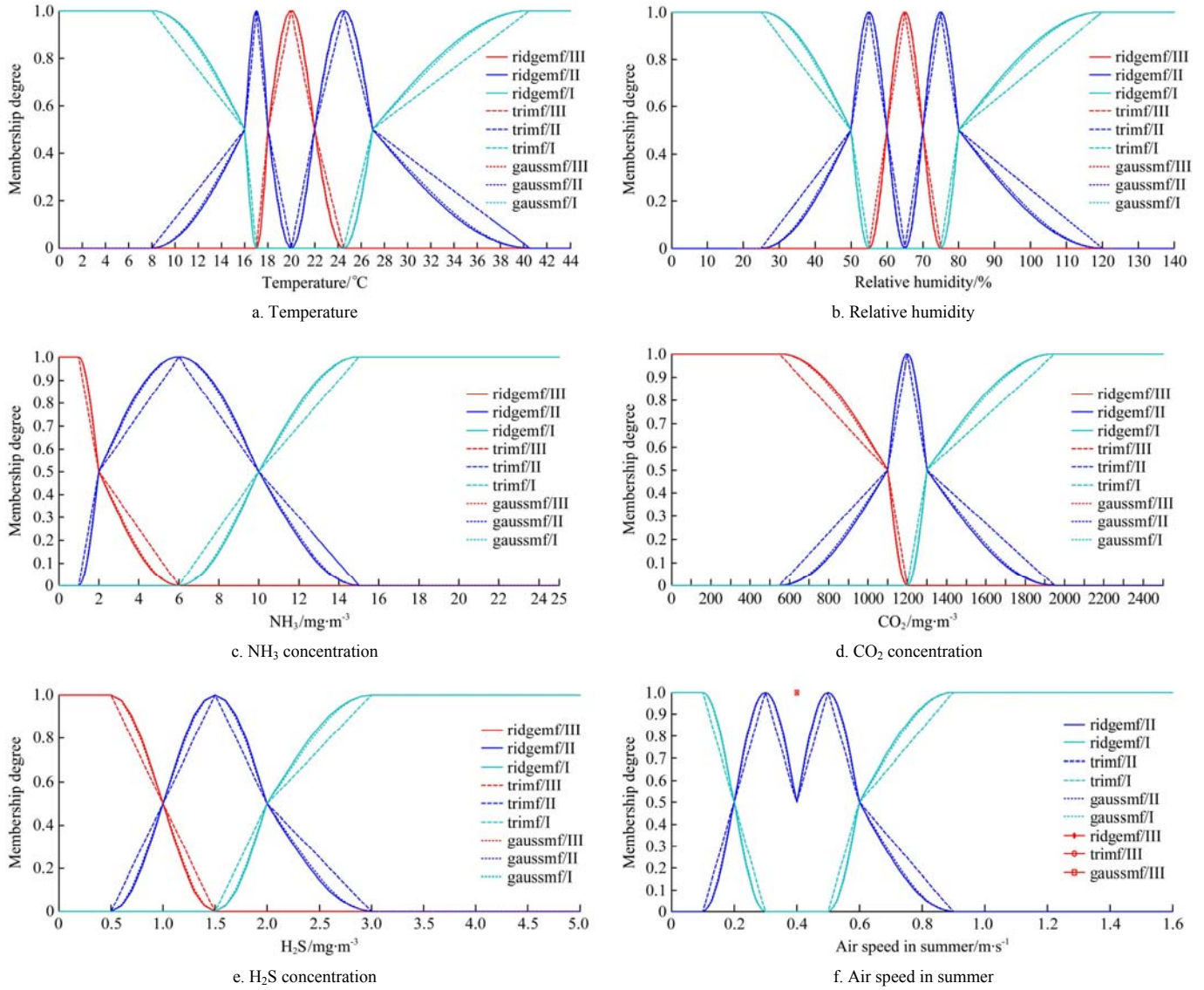
Based on the above construction method and evaluation standard listed in Table 3, the MFs of multiple environmental parameters in each interval can be constructed by using three basic types of MFs of ridgemf, trimf, and gaussmf (Figure 7).

2.5   Development of the evaluation model

IAHP and FCE were introduced for the establishment of the evaluation model by using a 5-step process as follows:

1) Determination of the evaluation factor set I

Determine the factors set $I=\{u_1, u_2, u_3, u_4, u_5, u_6\}$ which denotes temperature, relative humidity, concentrations of NH_3, CO_2, and H_2S, and air speed, respectively.

2) Foundation of the comment set J

The element of comment set $J=\{v_1, v_2, v_3\}$ can be a qualitative or quantified value, which is exploited to describe the grade of each evaluation factor. The comment set in this study consists of three criteria, namely Comfortable, Medium, and Poor, which are denoted by v_1, v_2, and v_3, respectively.

3) Determination of the membership matrix R

The membership functions are constructed according to the evaluation standard. Thus, the membership matrix R of the evaluation factors can be expressed as follows:

Note: m_i and n_i ($i=0,1,2\ldots k$) mean the endpoint of an interval; $\mu_i^{(j)}$ ($i=1,2\ldots k, j=1,2,3,4$) means the j-th membership function of i-th comfortable degree.

Figure 6   Constructed process of membership functions by combining wide and narrow modes

a. Temperature

b. Relative humidity

c. NH$_3$ concentration

d. CO$_2$ concentration

e. H$_2$S concentration

f. Air speed in summer

Note: "III" represents comfortable, "II" represents medium, and "I" represents poor.

Figure 7   Representation of ridgemf, trimf and gaussmf type MFs of six environmental factors

$$\boldsymbol{R} = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} = (r_{ij})_{6\times3} \quad (12)$$

where, r_{ij} denotes the possibility of appraising the i-th evaluation factor with the j-th criterion. In this study, the membership matrixes of the six evaluation factors (R_1, R_2, R_3, R_4, R_5, and R_6) are calculated via different membership functions.

4) Determination of the weighting vector ω

The weighting vector refers to the relative prominence degree of the evaluation factor. In this study, the weighting vector $\omega=\{w_1, w_2, w_3, w_4, w_5, w_6\}$ is calculated by using the IAHP.

5) Determination of the comprehensive judgement matrix A

The final comprehensive judgement matrix A is synthesized by combining the weighting vector ω with the membership matrix R, as shown in Equation (13). Moreover, the evaluation results of the comfort level are determined according to the principle of maximum membership degree.

$$\boldsymbol{A} = \boldsymbol{\omega} \times \boldsymbol{R} = [w_1, w_2, \cdots, w_6] \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \\ r_{41} & r_{42} & r_{43} \\ r_{51} & r_{52} & r_{53} \\ r_{61} & r_{62} & r_{63} \end{bmatrix} = [a_1, a_2, a_3] \quad (13)$$

where, ω represents the weighting vector of evaluation index; R refers to the membership matrix; A stands for the comprehensive judgement matrix.

2.6 Model validation

To verify the effectiveness of the proposed IAHP-FCE model in terms of the evaluation of multiple environmental factors, the single factor evaluation (SFE) model was also employed[28] as Equation (14).

$$a_m = \underset{i=1}{\overset{n}{Max}}\, \omega_i \times \mu_{i,m} \quad (14)$$

where, a_m denotes the evaluation result of the i-th environmental factor, m=1, 2, 3; ω_i represents the weight of the i-th environmental factor, as shown in Equation (11); $\mu_{i,m}$ stands for the membership degree of the i-th environmental factor.

3   Results and discussion

3.1   Difference analysis of the membership degree

The MFs of the environmental factors are constructed, as shown in Figure 7.   And environmental data of lactating sow house were downloaded from the Aliyun server system, as shown in Figure 3.   In this study, an example of a cold day was selected. The membership degree of each evaluation index was calculated by substituting the environmental parameters into the MFs (Figure 8). It can be seen that there were some differences in the description of the comfortable degree when using various types of MFs.   In addition, the membership degree of each environmental factor at a certain moment reflected the true conditions of the comfort level of lactating sows.

For example, at 7:00 a.m. on the typical cold day (Figure 3), the temperature, relative humidity, concentrations of NH_3, CO_2, and H_2S, and air speed were 18.6°C, 39.3%, 14 mg/m^3, 2587 mg/m^3, 0.52 mg/m^3, and 0.43 m/s, respectively.   The membership degree of each environmental factor was calculated by using different types of MFs (Figure 7).   However, as shown in Table 5, the fuzzy membership values are different from each other when using different types of MFs, e.g., the fuzzy membership values of the temperature and the H_2S concentration belonging to Grade III and II, the fuzzy membership values of relative humidity and NH_3 concentration belonging to Grade II and I.   The fuzzy membership

values of each environmental factor were calculated by using three different membership functions of ridgemf, gaussmf, and trimf with the calculation results shown in Figure 8.

Table 5   Fuzzy membership values of each evaluation factor using different types of MFs

Evaluation index	Comfortable degree	ridgemf	gaussmf	trimf
Temperature	III	0.7270	0.7136	0.6500
	II	0.2730	0.2864	0.3500
	I	0	0	0
Relative humidity	III	0	0	0
	II	0.1886	0.2018	0.2860
	I	0.8114	0.7982	0.7140
NH_3	III	0	0	0
	II	0.0245	0.0272	0.1000
	I	0.9755	0.9728	0.9000
CO_2	III	0	0	0
	II	0	0	0
	I	1	1	1
H_2S	III	0.9990	0.9989	0.9800
	II	0.0010	0.0011	0.0200
	I	0	0	0
Air speed	III	0	0	0
	II	0	0	0
	I	1	1	1

a. Temperature

b. Humidity

c. NH_3

d. CO_2
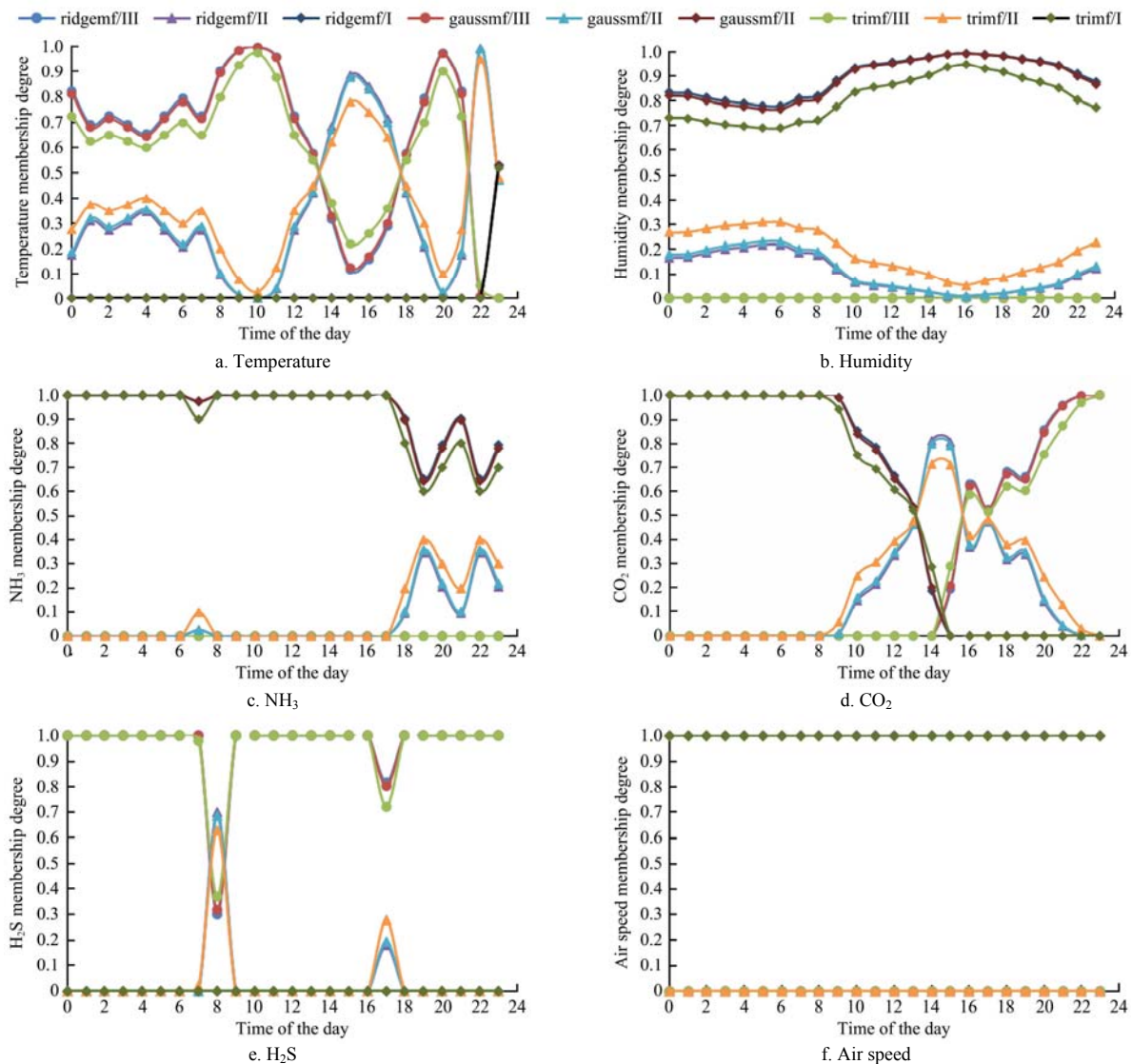
e. H_2S

f. Air speed

Figure 8   An example of membership degrees of each evaluation index using different types of membership functions on a cold day

3.2   Consistency analysis of the evaluation result

The selection of different types of MFs results in different r_{ij} and single factor evaluation matrix $R_i=(r_{i1}, r_{i2}, r_{i3})$.   Ultimately, the membership matrix $\boldsymbol{R}$ is also different.   In this study, the six evaluation factors have three evaluation matrixes $R_i=(r_{i1}, r_{i2}, r_{i3})$, respectively.   Specifically, the membership matrix $\boldsymbol{R}$ has 729 different structures based on permutation and combination.   In the case that the combination of ridgemf, gaussmf, trimf, ridgemf, gaussmf, and trimf type membership functions was chosen randomly among the six influencing factors, the total membership matrix was expressed as follows:

$$\boldsymbol{R}=\begin{array}{c} \\ u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{array}\begin{array}{ccc} v_1 & v_2 & v_3 \\ \left[\begin{array}{ccc} 0.7270 & 0.2730 & 0 \\ 0 & 0.2018 & 0.7982 \\ 0 & 0.1000 & 0.9000 \\ 0 & 0 & 1 \\ 0.9989 & 0.0011 & 0 \\ 0 & 0 & 1 \end{array}\right] \end{array} \quad (16)$$

Combining Equqations (14), (16), and the weighting vectors shown in Equation (11), the ultimate comprehensive judgement matrix was obtained as follows:

$$A = (0.4339, 0.1897, 0.3763) \quad (17)$$

It can be seen clearly that the maximum membership degree was 0.4339.   According to the principle of maximum membership degree, the comfortable degree of lactating sow belongs to Grade III, in another word, the sow house environment was "Comfortable".

In addition, in the case that the combination of gaussmf, trimf, ridgemf, gaussmf, trimf, and ridgemf type membership functions was chosen randomly among the six influencing factors, the total membership matrix was expressed as follows:

$$\boldsymbol{R}=\begin{array}{c} \\ u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \\ u_6 \end{array}\begin{array}{ccc} v_1 & v_2 & v_3 \\ \left[\begin{array}{ccc} 0.7136 & 0.2864 & 0 \\ 0 & 0.2860 & 0.7140 \\ 0 & 0.0245 & 0.9755 \\ 0 & 0 & 1 \\ 0.9800 & 0.0200 & 0 \\ 0 & 0 & 1 \end{array}\right] \end{array} \quad (18)$$

The ultimate comprehensive judgement matrix A = (0.4339, 0.1897, 0.3763) was obtained.   In the same way, the comfortable degree of lactating sows also belongs to Grade III, in another word, the sow house environment was "Comfortable".

Furthermore, a consistent conclusion can be drawn when using other random combinations of membership functions.   The comfort level of lactating sows was also "Comfortable", indicating that, despite different membership degrees, a consistent conclusion can be drawn when different basic functions were employed for the construction of the MFs of the evaluation factors.   Therefore, the problem of a random selection of the membership function was solved in the fuzzy comprehensive evaluation, and a new method for the construction of the membership function was provided.

3.3   Application of the comfort evaluation model

A comfort evaluation model of multiple environmental factors was established by using the environmental data in Figure 3. Figures 9 and 10 illustrate the maximum membership degree of the comfort level and the final evaluation results, respectively.

As can be seen from Figure 9, regardless of whether the weather was cold or hot, there were differences between the fuzzy membership values of the comfortable level when using different membership functions.   Nevertheless, the evaluation result was unique at every moment according to the principle of maximum membership degree.
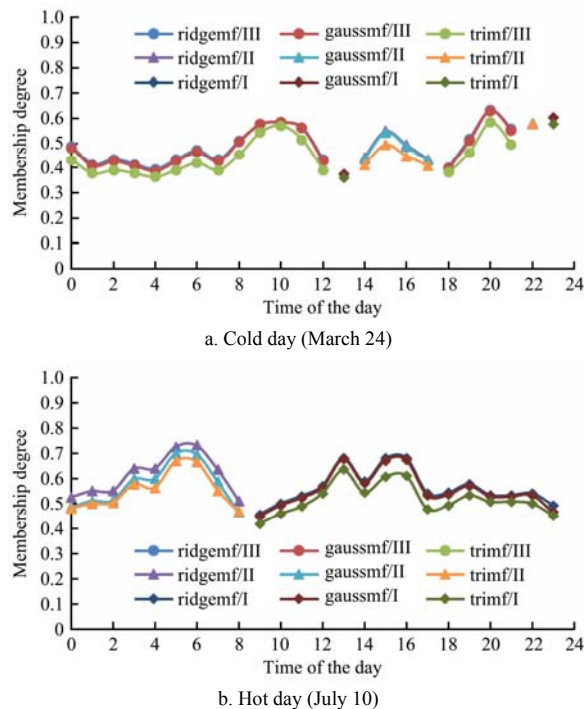

a. Cold day (March 24)

b. Hot day (July 10)

Figure 9   Membership degree of the comfort level of lactating sows

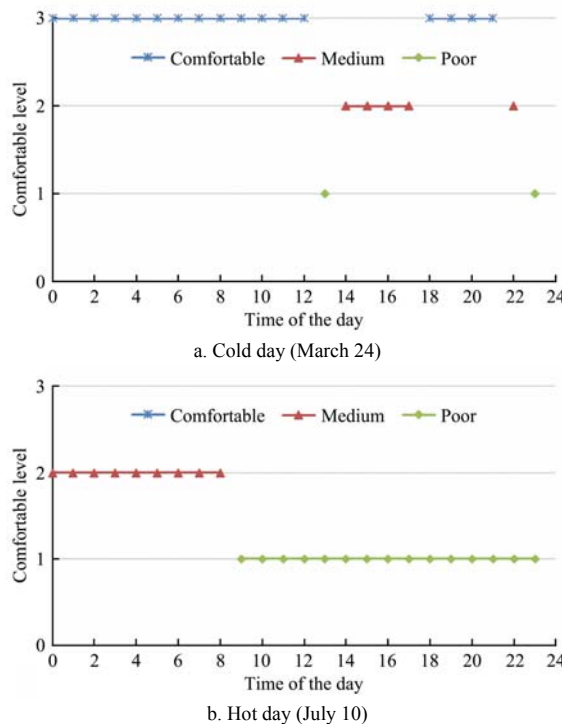a. Cold day (March 24)

b. Hot day (July 10)

Figure 10   Fuzzy comprehensive evaluation results for lactating sow house

It can be easily found that according to the definition of comfort levels, most of the comfort levels were "Comfortable" on cold days, but "Poor" on hot days.   However, there were some differences between Figures 10a and 10b, and more explanations were given as follows by the comparison with Figure 3.

On the typical cold day, there were two periods (0:00 to 12:00 and 18:00 to 21:00) when the evaluation results were "Comfortable".

During these two periods, although the relative humidity, NH_3 concentration, and air speed were within the range of "Poor", the temperatures were between 18.2°C and 21.4°C, which were in the range of "Comfortable", and most of the H_2S concentration was also in the range of "Comfortable". From 14:00 to 17:00, the comfortable levels of indoor air quality were "Medium", the reason was that during this period, the temperatures were between 22.6°C and 23.4°C, the relative humidity was between 27.6% and 29.8%, the air speed was between 0.53 m/s and 0.75 m/s, and the concentrations of CO_2, H_2S and NH_3 were between 1006 mg/m³ and 1257 mg/m³, 0.15 mg/m³ and 0.78 mg/m³, and lower than 18 mg/m³, respectively. In particular, after 18:00 p.m., the temperatures significantly decreased to 17.1°C at 22:00, and further to 15.7°C at 23:00 due to the continuous increase of air speed. Although the concentrations of NH_3, CO_2, and H_2S were lower than 12 mg/m³, 582 mg/m³, and 0.1 mg/m³, respectively, the comfort levels were "Medium" at 22:00 and "Poor" at 23:00.

On the typical hot day, from 9:00 to 23:00, most of the comfortable levels were "Poor", mainly because the temperatures were higher than 29°C, that is, within the range of "Poor". Although the H_2S concentration was in the range of "Comfortable", all the NH_3 concentrations and most of the CO_2 concentrations were within the range of "Medium". However, there was still a period of time when the comfortable levels of indoor air quality were "Medium". For example, from 0:00 to 8:00, the temperatures were between 25.0°C and 27.6°C, the relativity humidity was between 72.3% and 85.5%, the concentrations of NH_3, CO_2, and H_2S were between 2.68 mg/m³ and 5.56 mg/m³, 1052 mg/m³, and 1175 mg/m³, and lower than 0.1 mg/m³, respectively, and the air speed was lower than 0.77 m/s.

It can also be seen from Figure 10 that the temperature is indeed the most important factor, and plays a major role in sow house environment. However, indoor air quality is determined by multiple environmental factors such as temperature, relative humidity, concentrations of NH_3, CO_2, and H_2S, and air speed at a certain moment, instead of a single environmental factor.

3.4 Comparison of different evaluation methods

In this study, the single-factor evaluation model was also employed for comparison. To facilitate the evaluations of consistencies and differences between the IAHP-FCE and SFE models, the correlation coefficient of the respective assessment results was employed. For example, the correlation coefficient of 0.722 is high on the typical cold day, indicating that the evaluation results of IAHP-FCE model were consistent with the popular SFE model. The correlation coefficient of 0.662 is not high on the typical hot day, which means that there were still some differences between the two models. In addition, the average correlation coefficient is 0.874 on both cold and hot days. Therefore, the evaluation results of the two models match well. The IAHP-FCE model can be employed for the assessment of the comfortable level of lactating sows, and an applicable model is provided for the control of environmental parameters.

Besides, the IAHP-FCE model is more effective than the SFE model, especially for the assessment of uncertainties and ambiguousness of multiple environmental factors. For example, at the four time-points (0:00, 1:00, 2:00, and 8:00) on the hot day, as shown in Table 6, the evaluation results of the IAHP-FCE and SFE models were "Medium" and "Poor", respectively. The respective indoor temperatures were 27.6°C, 27.2°C, 27.4°C, and 27.3°C, which were within the "Poor" range. The corresponding relative humidity was 72.3%, 72.8%, 73.2%, and 80.1%, which

was within the range of "Comfortable" or "Medium". In addition, the corresponding concentrations of NH_3 and H_2S were within the "Comfortable" range, and the corresponding air speed was slightly above the "Poor" range. The evaluation results demonstrate that the IAHP-FCE model considers the impacts of the multiple environmental factors comprehensively, instead of the temperature independently, because they are all important to animal health and welfare.

Table 6   Comparison between the evaluation results using the SFE and IAHP-FCE models on the two typical days

Time	Results on the cold day		Results on the hot day	
	SFE	IAHP-FCE	SFE	IAHP-FCE
0:00	III	III	I	II
1:00	III	III	I	II
2:00	III	III	I	II
3:00	III	III	II	II
4:00	III	III	II	II
5:00	III	III	II	II
6:00	III	III	II	II
7:00	III	III	II	II
8:00	III	III	I	II
9:00	III	III	I	I
10:00	III	III	I	I
11:00	III	III	I	I
12:00	III	III	I	I
13:00	III	I	I	I
14:00	II	II	I	I
15:00	II	II	I	I
16:00	II	II	I	I
17:00	II	II	I	I
18:00	III	III	I	I
19:00	III	III	I	I
20:00	III	III	I	I
21:00	III	III	I	I
22:00	II	II	I	I
23:00	II	I	I	I

3.5 Suggestions on the environmental control of sow house

Based on the evaluation results of the environmental comfort of lactating sow houses, some suggestions are provided.

1) The evaluation model established in this study can be used for a sensitive assessment. The time-step in this study was set to 1 h, while shorter time steps, such as 30 min, 10 min, or 1 s can be applied to the real-time evaluation of indoor air quality. In addition, this model can be integrated into the environmental control system, such as the cooling and heating control system, which should play a key role in the real-time control of multiple environmental parameters.

2) Due to the coupling effects of the environmental factors, such as temperature, humidity, concentrations of harmful gases, and air speed, the concentrations of harmful gases decrease with the increase of air speed. However, the indoor temperature also decreases on cold day, which could induce a stress response and health problems. Therefore, it is necessary to compensate for the heat loss caused by ventilation based on the energy balance equation. Prolonging the heating time of the heating apparatus is one of the effective measures.

3) The actual values of environmental comfort of lactating sows could be calculated using the historical data based on the IAHP-FCE model. The historical data and the values of environmental comfort could be employed as training and testing data, and then a prediction model of environmental comfort of

lactating sows could be developed based on machine learning and deep learning algorithms. Therefore, breeders could make the decision according to the prediction results. In the case that the prediction results show that the comfort level is "Poor" in the future, breeders could exploit suitable control measures in advance.

4 Conclusions

The following conclusions can be drawn from this study.

1) To provide a scientific basis for a real-time evaluation of the comfort level of lactating sows, IAHP was employed to determine the weights of multiple environmental factors combined with the experiences of experts in animal husbandry;

2) Various types of functions were employed based on the proposed membership functions construction method, and the influence of various membership functions on the evaluation results was discussed. Although there are different descriptions of the ambiguity of the comfortable degree when using various types of membership functions, the evaluation results are unique and consistent. Therefore, various types of MFs were equivalent when evaluating the comfortable level of lactating sows. No matter which membership function is used for the evaluation of environmental comfort, consistent results can be obtained for the convenience of analysis;

3) Experimental validation of the two models was performed by using the same data sets. The IAHP-FCE model can more objectively and accurately reflect the actual conditions of the sow house environment compared with the SFE model. Thus, the IAHP-FCE model is proved to be more effective for the evaluation of the uncertainties and ambiguousness of multiple environmental factors;

4) A graphical user interface (GUI) of the environmental comfort evaluation system was developed for the calculation of the comfort level using the real-time environmental data, providing a useful basis for the real-time control of ventilation fan units, water curtains, and air treatment equipment.

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