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Research on Light Pollution Evaluation Modeling Based on Comprehensive Weights and FCE

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Abstract: Light pollution refers to the excessive or improper use of artificial light. Global light pollution poses environmental and health problems. Therefore, there is a need to develop light pollution metrics to measure light pollution levels and select effective intervention strategies. Firstly, the global light pollution related data in the past 5 years were selected to determine 4 primary indicators, such as interference light pollution, visual light pollution, sky brightness, and biological light damage, as well as 48 secondary indicators, such as population. Then, the second-level indicators were downgraded by combining principal component analysis, and 12 second-level indicators with important impacts were screened out. After that, AHP, entropy weight method and CRITIC method were used to synthesize the light pollution weight evaluation model by comprehensively assigning weights and initially determining the evaluation interval of light pollution level. At the same time, the multilevel fuzzy comprehensive evaluation method was used to test and to determine the light pollution risk level of a location by obtaining five light pollution evaluation levels based on the upper and lower limits of the evaluation interval. In addition, the cases of Cocoa Sicily Nature Reserve, Xizang, Philadelphia, and New York as the location of protected land, rural communities, suburban communities, and urban communities, respectively, were substituted into the light pollution weight evaluation model to obtain the light pollution scores and grades for each area, respectively. Finally, the four regions are compared and analyzed to draw conclusions and give suggestions and strategies to intervene in light pollution.

1. Introduction

Light pollution is a new source of environmental pollution from the excessive use of artificial light(Li Jieqong, 2023)[1].This pollution phenomenon includes light trespass, over-illumination, and light clutter. While promoting nighttime economic development, artificial light also brings a series of environmental problems and health problems, such as light interference to vehicles and pedestrians, light pollution to residents, light intrusion to plants and animals, and effects on people's physical health and mental health. There is an urgent need for regional governments to introduce laws, regulations and policies to provide a basis for light pollution prevention and control and to achieve sustainable economic and environmental development in all regions.However, currently the world has not yet formed a unified technical standard for light pollution, and light pollution cannot be effectively controlled when the environmental protection department is unable to operate(Han Z Z et al., 2023)[2].For ecologically fragile areas, light pollution is more likely to cause problems, while ecologically homogenous and sparsely populated areas are much less likely to be affected by light pollution than other areas(BURT C S et al., 2023)[3].Although the research on light pollution is deepening, the prevention and control work is still in its infancy. There are no in-depth results on light pollution prevention policies, standards and norms. Although there are more studies on the analysis of light intensity and urban glare, there are few risk analysis studies that consider the actual impact factors of light pollution(Li Yinghua et al., 2023)[4].

2. Research on light pollution evaluation model

2.1 Selection of indicators

Firstly, the light pollution related data of different regions of the world for the last 5 years are selected from National Geophysical Data Center and extreme outliers and missing values are removed[5]. Secondly, the dataset is utilized to build a model. Four first-level evaluation indicators were selected to evaluate the magnitude of light pollution. The four first-level indicators are: interference light, visual pollution, sky glow, and biological light damage[6].Twelve secondary indicators are subordinated to each primary indicator. However, the evaluation polarity of the second-level indicators under these first-level indicators is not the same, so before building the evaluation model, we should first make polarity judgment, carry out indicator forwarding, and transform all the indicators into great indicators.The data collected for each impact indicator were dimensionless.

$$r_{ij} = \left(X_{ij} - min\{X_{ij}\}/\left(max\{X_j\} - min\{X_j\}\right)\right) \tag{1}$$

$$r_{ij} = \left(\{max\ X_{ij}\} - X_{ij}\right)/\left(max\{X_j\} - min(X_j)\right) \tag{2}$$

2.2 Principal component analysis (PCA)

Interference light pollution is used as an example to illustrate the principal component analysis dimensionality reduction process. In this way, X_1 , X_2 , X_3 , X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, X_{11} and X_{12} respectively represent population,the number of traffic accidents, effects of light trespass on residents,over-illumination,stroboscopic effect,light clutter,light interference for astronomy,the distance of the light from the house,affected by light,ultraviolet radiation interference and degree of thermal radiation interference.

Calculate the correlation matrix, $r_{ij}$is the correlation coefficient of the original variables $x_i$and x_j. The eigenvalues and eigenvectors principal component contribution z_i, cumulative contribution, and principal component loadings are calculated[7]. This further calculates the principal component scores, and the principal component fragmentation plot for each variable is shown by Figure 1.Four influencing factors with a contribution rate greater than 80% were obtained: population, the number of traffic accidents affected by light, effects of light trespass on residents, over-illumination. Therefore, this paper uses these 4 indicators as principal components instead of the original 12 influencing factors, as shown in Figure 2 below.

$$R=\begin{bmatrix} r_{11} & \cdots & r_{1p} \\ \vdots & \ddots & \vdots \\ r_{p1} & \cdots & r_{pp} \end{bmatrix} \quad (3)$$

$$r_{ij} = \frac{\sum_{k-1}^{n}(x_{ki}-\overline{x_i})(x_{kj}-\overline{x_j})}{\sqrt{\sum_{k-1}^{n}(x_{ki}-\overline{x_i})^2 \sum(x_{kj}-\overline{x_j})^2}} \quad (4)$$

$$r_i = \sum_{k=1}^{p} \gamma_k \ (i = 1,2,3,\ldots,p) \quad (5)$$

$$\sum_{k}^{m} \gamma_k \Big/ \sum_{k}^{p} \gamma_k \quad (6)$$

$$p(Z_k, X_i) = \sqrt{r_k} e_{ki} (i, k = 1,2 \ldots p) \quad (7)$$

$$z = \begin{bmatrix} z_{11} & \cdots & z_{1m} \\ \vdots & \ddots & \vdots \\ z_{n1} & \cdots & z_{nm} \end{bmatrix} \quad (8)$$

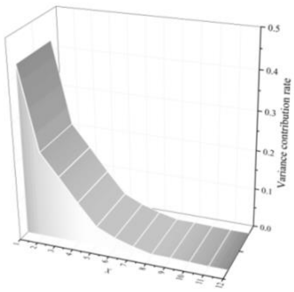

Figure 1: Principal component gravel plot

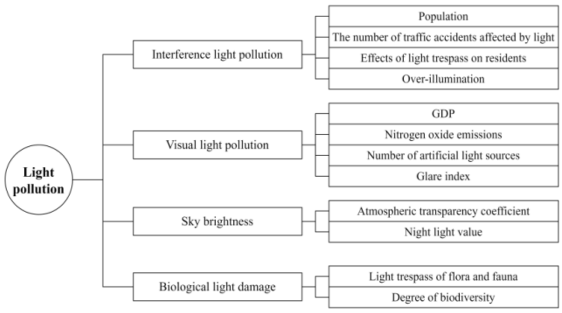

Figure 2: Indicators filtered by principal components

2.3 Comprehensive weighting method

2.3.1 Analytic hierarchy process (AHP)

Analytic Hierarchy Process (AHP) is a simple method to make decisions on some more complex and fuzzy problems. The selected indicators can be divided into three categories[8]. The objective level includes the degree of influence of each factor on light pollution. The criterion level includes interference light pollution, visual light pollution, sky brightness, and biological light damage. The plan layer refers to the degree of influence of each factor on light pollution, which is categorized into high, medium and low degree of influence, as shown in Figure 3.

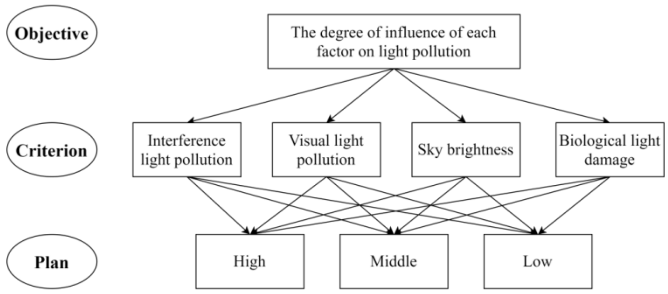

Figure 3: AHP hierarchy

(1) Determination of the weight of the impact factors of the first-level indicators

The criterion level judgment matrix is built and the maximum eigenvalue is obtained as λ_{max}=4.0104.The corresponding eigenvector W^{-T}={0.7766 0.4163 0.2243 0.4163}.Consistency indicators and consistency ratios are calculated.CI=0.0035， CR=0.0038<0.1， the consistency of this judgment matrix was considered acceptable. After normalization, it is shown in Table 1.

$$\begin{bmatrix} 1 & 2 & 3 & 2 \\ 0.5 & 1 & 2 & 1 \\ 0.33 & 0.50 & 1 & 0.5 \\ 0.5 & 1 & 2 & 1 \end{bmatrix} \tag{9}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{10}$$

$$CR = \frac{CI}{RI} \tag{11}$$

Table 1: Weight table of each influence factor of the first-level indicator

Impact Factor	Weight
Interference light pollution	0.4236
Visual light pollution	0.2471
Sky brightness	0.1223
Biological light damage	0.2070

(2) Determination of the weight of each influence factor in the secondary index interference light

$$\begin{bmatrix} 1 & 1 & 2 & 3 \\ 1 & 1 & 1 & 2 \\ 0.5 & 1 & 1 & 1 \\ 0.33 & 0.5 & 1 & 1 \end{bmatrix} \tag{12}$$

The maximum eigenvalue is obtained as λ_{max} =4.0813. The corresponding eigenvector is W^{-T}={0.6983 0.5353 0.3797 0.2857}.CI=0.0271， CR=0.0301<0.1, the consistency of this judgment matrix was considered acceptable. By analogy, the weights of each influencing factor in the remaining three categories of primary indicators visual light pollution, sky brightness, and biological light damage, can be obtained, as shown in Table 2.

Table 2: Weight table of each influence factor of the secondary index

Index	Weight	Index	Weight
Population	0.3677	Effects of light trespass on residents	0.2000
The number of traffic accidents affected by light	0.2819	Over-illumination	0.1504

2.3.2 Entropy weighting method and CRITIC weighting method

The weights of each indicator obtained from AHP, entropy weighting method and CRITIC weighting method were synthesized and processed as shown in Table 3.

Table 3: Combined weights of light pollution indicators

Tier 1 Indicators	Combined weights(%)	Tier 2 Indicators	AHP (%)	Entropy method (%)	CRITIC weighting (%)	Combined weights(%)
Interference light pollution	42.36	Population	36.77	29.25	39.80	35.27
		The number of traffic accidents affected by light	28.19	15.23	15.23	19.55
		Effects of light trespass on residents	20.00	23.61	25.33	22.98
		Over-illumination	15.04	21.37	19.64	18.68
Visual light pollution	24.71	GDP	38.35	24.81	18.35	27.17
		Nitrogen oxide emissions	14.75	25.65	16.41	18.94
		Number of artificial light sources	10.52	26.71	28.61	21.95
		Glare index	36.38	22.83	36.64	31.95
Sky brightness	12.23	Atmospheric transparency coefficient	25.00	39.37	46.32	36.90
		Night light value	75.00	60.63	53.70	63.11
Biological light damage	20.70	Light trespass of flora and fauna	83.33	51.22	51.22	61.92
		Degree of biodiversity	16.67	48.78	48.78	38.08

2.4 Synthesis and operation of the light pollution degree weighting model

Table 4 below shows the indicators of light pollution and their significance.Based on the previous paper, the dimensionless values of the secondary indicators u_i are obtained by data preprocessing in this paper.After that, the differences of attribute values among some indicators are considered. For example, u_{23} is the number of artificial light sources, and the higher the measured value, the higher the degree of light pollution, which is a positive indicator; while $u_{31}$is the atmospheric transparency coefficient, and the higher the value, the lower the degree of light pollution, which is a negative indicator. Based on this, the negative indicator needs to be positivized in the next step.That is, the value 1 is subtracted from the dimensionless value u_i, and the forwarded measured value y_i^* is thus obtained.Combined with the existing weights, the light pollution degree weighting model is synthesized. The following is a synthesis of the primary and secondary indicators with the following equations.The formula u_i indicates the standardized value of the first-level index, w_i is the weight of the second-level index corresponding to u_i, and n is the number of items of the first-level index.In turn, the final numerical results of the light pollution degree index P can be obtained. U_i is the numerical result of the first-level indicator, W_i is the weight of the first-level indicator corresponding to U_i, and N is the number of items of the first-level indicator[9].Finally, based on the collected data and using the model results, the score of the area with the lowest light pollution level of 2.7164 was initially selected as the lower limit of the evaluation interval, and the score of the area with the highest light pollution level of 4.3409 was used as the upper limit of the evaluation interval. In order to verify the reasonableness of the upper and lower critical limits of the evaluation interval, the multilevel fuzzy comprehensive evaluation method was utilized for testing.

Table 4: Light pollution indicators and their significance

Index	Index significance	Index	Index significance
U_1	Interference light pollution	U_2	Visual light pollution
U_3	Sky brightness	U_4	Biological light damage
u_{11}	Population	u_{12}	The number of traffic accidents affected by light
u_{13}	Effects of light trespass on residents	u_{14}	Over-illumination
u_{21}	GDP	u_{22}	Nitrogen oxide emissions
u_{23}	Number of artificial light sources	u_{24}	Glare index
u_{31}	Atmospheric transparency coefficient	u_{32}	Night light value
u_{41}	Light trespass of flora and fauna	u_{42}	Degree of biodiversity

$$y_i^* = 1 - u_i \tag{13}$$

$$U_i = \sum_{i=1}^{n} u_i \cdot w_i \tag{14}$$

$$P = \sum_{i=1}^{N} U_i \cdot W_i \tag{15}$$

$$\begin{cases} U_1 = 0.3527u_{11} + 0.1955u_{12} + 0.2298u_{13} + 0.1868u_{14} \\ U_2 = 0.2717u_{21} + 0.1894u_{22} + 0.2195u_{23} + 0.3195u_{24} \\ U_3 = 0.3690u_{31} + 0.6311u_{32} + 0000000000000000000 \\ U_4 = 0.6192u_{41} + 0.3808u_{42} + 0000000000000000000 \end{cases} \tag{16}$$

$$P=0.4236U_1+0.2471U_2+0.1223U_3+0.2070U_4 \tag{17}$$

2.5 Multi-level fuzzy comprehensive evaluation method

2.5.1 Constructing the affiliation function

Using the triangular fuzzy distribution graph, the affiliation function is determined based on the 5-level semantic scale of the score (as shown in Equation 16)[10] .

$$M_j(X_i) = \begin{cases} 1 & (x_i = a_j)(j = 2,3,4) \\ X_i - a_{j-1} & (a_{j-1} + 0.5 < x_i < a_j) \\ a_j - x_i & (a_{j-1} < x_i < a_{j-1} + 0.5, a_j + 0.5 < x_i < a_{j+1}) \\ a_{j+1} - x_i & (a_j < x_i < a_j + 0.5) \\ 0 & (x_i \le a_{j-1}, x_i \ge a_j + 1) \end{cases} \tag{18}$$

2.5.2 Determining the subjective evaluation level

Based on the collected data, the score of the area with the lowest level of light pollution among them is the lower limit of the evaluation interval, and the score of the area with the highest level of light pollution among them is the upper limit of the evaluation interval, and the average value of the scores of each factor is substituted into Eq. 18, to establish a multilevel fuzzy evaluation model of light pollution.

$$A=\{0.3527\ \ 0.1955\ \ 0.2298\ \ 0.1868\} \tag{19}$$

$$R_{B_1}=\begin{bmatrix}0.00 & 0.01 & 0.05 & 0.16 & 0.78\\ 0.00 & 0.13 & 0.17 & 0.20 & 0.50\\ 0.00 & 0.00 & 0.04 & 0.27 & 0.69\\ 0.00 & 0.16 & 0.19 & 0.29 & 0.36\end{bmatrix} \tag{20}$$

$$B_1=A\cdot R_{B_1} \tag{21}$$

$$B=A\cdot R \tag{22}$$

The composite score value of the area with the highest degree of light pollution and the composite score value of the area with the lowest degree of light pollution are shown below. Then the upper and lower limit critical scores of the evaluation interval obtained through the multilevel fuzzy comprehensive evaluation method are similar to the scores obtained by the light pollution weight evaluation model, i.e., the rationality of the upper and lower limit critical scores of the evaluation interval is verified. The light pollution score of 2.7 was finally determined as the lower limit of the evaluation interval, and the light pollution score of 4.35 as the lower limit of the evaluation interval. Therefore, the evaluation system of light pollution was divided into five levels, as shown in Table 5:

$$V=1\times0.0018+2\times0.0407+3\times0.1465+4\times0.3126+5\times0.5170=4.3581 \tag{23}$$

$$V=1\times0.0018+2\times0.0407+3\times0.1465+4\times0.3126+5\times0.5170=4.3581 \tag{24}$$

Table 5: Light pollution evaluation level

Level	*I*	*II*	*III*	*IV*	*V*
Score	Less than 2.7	2.7-3.25	3.25-3.8	3.8-4.35	More than 4.35

3. Case study analysis of light pollution in protected land locations, rural communities, suburban communities, and urban communities

3.1 A protected land location

Qinghai Cocosily National Nature Reserve is located in the northwest of China's Qinghai Province, bordering with Xinjiang and Xizang, with an area of 45,000 square kilometers. It is the world's best-preserved nature reserve in terms of pristine ecological environment, and also one of the largest nature reserves built in China, with the highest altitude and the richest wildlife resources. Figure 4 is a satellite image of nighttime lights in Cocosily Nature Reserve.Based on the collected local data related to the Cocoa Slippery Nature Reserve in Qinghai Province, China, combined with the established weighting model of the degree of light pollution, a light pollution score is obtained P_1=0.3608.According to the evaluation system of light pollution, it belongs to Class *I* light pollution. Cocoa Slippery is one of the richer areas in China in terms of animal resources, possessing as many as 230 kinds of wild animals. The population density is large and the number is high. At the same time, the average altitude of Cocosily reaches 4,600 meters, and most of the area is a "forbidden area for human beings", with a sparse population and a low level of economic development, so that the number of lights at night is very small, and the area covered by artificial light is extremely low. Therefore, the light pollution score of the region is extremely low, and the level of light pollution is the lowest.

3.2 A rural community

Xizang, the least populated province in China, is located on the southwestern border of the country, with an average altitude of more than 4,000 meters, a maximum width of about 1,000 kilometers from north to south and a maximum length of 2,000 kilometers from east to west, making it the world's largest and highest plateau, and is known as the "roof of the world". Its rural communities are less accessible to urban residents. Figure 5 is a satellite image of nighttime lighting in Xizang, China. Based on the collected local data of Xizang, China, combined with the established light pollution degree weighting model, the light pollution score is obtained as follows P_2=2.7284. According to the evaluation system of light pollution, it belongs to class *II* light pollution. Xizang has the world's first plateau, 80% of which belongs to the no-man's land of the Gobi Desert. The climate is dry and cold, coupled with the lack of oxygen and thin air. The climate is not suitable for human habitation. In addition, for historical reasons, the Xizang plateau has been sparsely populated since ancient times. And because of the harsh geographical environment hindered the socio-economic development of Xizang, but due to the more developed tourism industry in Xizang, led to the development of the region's night-time economy, the night lights are also increasing, the degree of light pollution to strengthen, but the overall index of light pollution is still on the low side.

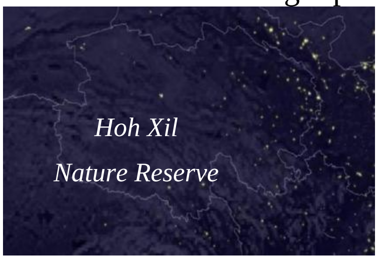

Figure 4: Satellite view of nighttime Lighting in the Cocosili Nature Reserve

Figure 5: Satellite map of Xizang night lights in China

3.3 A suburban community

Philadelphia, located in the southeastern part of the U.S. state of Pennsylvania, is Pennsylvania's largest city and city with the largest economy, as well as the fifth-largest city in the U.S. It is just across the river from New Jersey; the population of the Philadelphia metropolitan area totals 155,316,655, and the population of the metro area is more than 7,150,000 people. Its suburban communities are also densely populated, with well-traveled neighborhoods that facilitate access for city residents. Figure 6 is a satellite view of nighttime lighting in Philadelphia, USA. Based on the collected data related to Philadelphia, USA, combined with the established light pollution level weighting model, a light pollution score was obtained P_3=3.8825. According to the Light Pollution Rating System, it is under Class *III* light pollution. Philadelphia is the largest economic city in Pennsylvania. It is more densely populated and economically developed, and it is strategically located and surrounded by some large cities. As a result, the city has a high number of lights, a wide area covered by artificial light, and a high level of light pollution.

3.4 An urban community

New York City, part of the U.S. state of New York, is the largest city in the United States, with a total area of 1,214 square kilometers and five boroughs. As of April 2022, New York City has a total population of approximately 8,398,000, making it the most densely populated city in the United States.

New York City is the economic, financial, commercial, trade, cultural and media center of the United States and the world, and is one of the world's three major financial centers. Figure 7 is a satellite view of the nighttime lights of New York, USA. According to the collected relevant data of New York, USA, combined with the established light pollution degree weighting model, the light pollution score is obtained P_4=4.6840. According to the evaluation system of light pollution, it is classified as Class *V* light pollution. New York is recognized as the capital of the world, is the most populous city in the United States, more than a century, New York City has been the world's most important commercial and financial center. New York is the world's economic center, the economy and trade is very prosperous and developed, the city street lights about 250,000. The frequency of light use is very high, so the light pollution level index is much higher than the other three regions, and light pollution is the most serious.

Figure 6: Satellite view of nighttime lights in Philadelphia, USA

Figure 7: Satellite view of nighttime lights in New York, USA

3.5 Comparison of light pollution levels in the four regions

The 12 secondary indicators, such as population and GDP, of Cocos Creek scored the lowest of the four. This is because nature reserves are areas where natural ecosystems, rare and endangered wildlife and plants are protected and not affected by development. It is sparsely populated and has almost no artificial lights. It has the lowest scores for light disturbance, visual pollution, sky glow, and biological light damage. Therefore, its light pollution score is much lower than the other three, and it belongs to Class *I* light pollution.

Xizang scores second only to New York in the number of light-influenced traffic accidents and Light trespass of flora and fauna, and scores lower than Philadelphia and New York in the other 10 secondary indicators. This is due to Xizang's remote location, small population and relatively poor economic development, but it is located in a good environment with a large biome. Its biological light damage score is second only to New York, and its light interference, visual pollution, and sky glow scores are lower than those of New York and Philadelphia. Therefore, its light pollution score is second to Philadelphia and New York, and higher than Cocoanut Creek Nature Reserve, which is a class *II* light pollution.

Philadelphia scores second only to New York in 10 secondary indicators such as population and GDP. This is because Philadelphia is more densely populated, more economically developed, and its location is favorable, surrounded by some large cities. It scores second only to New York in light interference, visual pollution, and sky glow, and second only to New York and Xizang in biological light damage. Therefore, its light pollution score is second only to New York and belongs to level *III* light pollution.

New York has the highest scores among the three for 12 secondary indicators, such as population. This is because New York is densely populated, economically developed, with convenient transportation, very high frequency of light use, and extensive application of artificial light. It has the highest scores for light interference, visual pollution, sky glowing, and biological light damage. Therefore, its light pollution score is much higher than the other three, and it belongs to class *V* light pollution.Figure 8 shows the comparison of light pollution scores in the four regions.

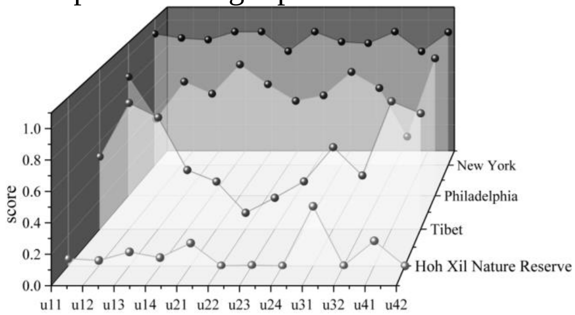

Figure 8: Scores of 12 secondary indicators for each of the four regions

4. Conclusions

Light pollution is a new source of environmental pollution after exhaust gas, waste water, waste residue and noise pollution, which brings a series of environmental and health problems. Regional governments urgently need to introduce laws related to environmental impact assessment of light pollution, so as to achieve a balance between economic and environmental protection, and to realize the sustainable development of the economy and the environment in each region. Therefore, there is a need to develop a widely applicable light pollution standard to measure light pollution levels in different regions, and to select effective intervention strategies to mitigate the impacts of light pollution.

In this paper, after synthesizing the actual light pollution research situation in various regions of the world, and combining the global light pollution prevention and control related literature, the following three feasible and effective light pollution intervention strategies are derived:

(1) Encourage scientific and technological innovation in the invention and design of lamps and lanterns, and use new technologies to reduce the harm of light pollution.

(2) Strengthen the ecological design of night lighting and rationalize the use of night lighting.

(3) Countries need to improve the legislation on light pollution control and formulate clear lighting standards.

Under the joint efforts of the world, light pollution can be effectively managed. The ecological environment can be further improved, and the beautiful starry sky can definitely come back.

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