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Construction of a Green-Comprehensive Evaluation System for Flotation Collectors

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Abstract: The evaluation of flotation reagents performs an important role in the selection and green application of reagents. The green indexes and effect indexes of flotation collectors were selected by data literature method, system analysis method, mathematical model method, and qualitative and quantitative analysis method, and the green evaluation system of flotation collectors, flotation effect evaluation system, and comprehensive evaluation system of flotation collectors were established. The normalization method and expert evaluation methods were adopted to obtain the grade classification of quantitative and qualitative indicators, respectively. The analytic hierarchy process (AHP) was used to determine the weight of secondary indicators and tertiary indicators of the evaluation system and the weight of indicators at a lower level. Applying the fuzzy comprehensive evaluation (FCE), the trapezoidal function is selected to determine the index affiliation, the index system score is calculated according to the weighted average principle, and finally, the established evaluation system is applied in an example. The example application shows that the comprehensive evaluation system of flotation collectors can make a comprehensive evaluation of collectors from the aspects of the greenness of reagent, flotation effect, and cost, and it has a strong target and practicality for collectors evaluation. The establishment of the system has a guiding significance for the selection and use of flotation collectors.

Keywords: collector; green evaluation; comprehensive evaluation; analytic hierarchy process; fuzzy comprehensive evaluation

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1. Introduction

In the Coal Industry Development Annual Report 2020, it was shown that the raw coal washing rate reached 74.1% in the past five years, which is 8.2 percentage points higher than that of 2015 [1–3]. A Flotation collector is a necessary reagent used in the coal flotation process, and with the increase in coal washing rate, the demand for flotation collectors in coal preparation plants is increasing [4,5].

The commonly used collectors for coal slurry flotation are kerosene, diesel oil, etc. Flotation collector has great safety and health hazards, such as storage collectors having a low flash point, flammable and explosive shortcomings, use with a strong irritating odor, and volatile, toxic disadvantages [6–8]. With the increase in the coal washing rate, the environmental and health impacts caused by the storage, transportation, and use of flotation collectors are getting more and more attention from related departments [9–11]. First, the flotation collector poses a hidden danger to the environment during production, transportation, and use [12,13]; second, the hazards caused by the environmental impact and health impact during water circulation in the coal processing plant are not treated, so the flotation collector can cause harm to the ecosystem around the plant and the flotation operators [14–16]. The flotation collector has the characteristics of a strong hazard, many types, and large dosage, so the establishment of a flotation collector evaluation system can do a good job of controlling the flotation collector from the source and also can promote the healthy and green development of a coal processing plant [4,17–19].

There are standards for flotation effect, carcinogenicity, acute toxicity, reproductive toxicity, and flash point of the flotation collector in the industry, but the evaluation is scattered and cannot evaluate the flotation collector systematically and comprehensively [20–23]. The green-comprehensive evaluation system can consider a flotation process as a whole and, through the decomposition of the overall flotation process, get various impacts of flotation collectors in manufacturing, transportation, storage, and use, then specifically analyze the connection between individual flotation and the whole, then make a scientific and reasonable evaluation of flotation collectors.

2. Flotation Collector Green Evaluation System

2.1. Selection of Indicators for Different Levels of Flotation Collector Green Evaluation System

Based on the usage of flotation collectors in coal preparation plants, a green evaluation system for flotation collectors was constructed using the Analytical Hierarchy Process (AHP). The basis for selecting green indicators for flotation collectors was established by referring to the safety data sheet for chemicals and the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) [24], and a "1-4-25" green evaluation system for flotation collectors was formed. The evaluation index system at all levels is shown in Figure 1.

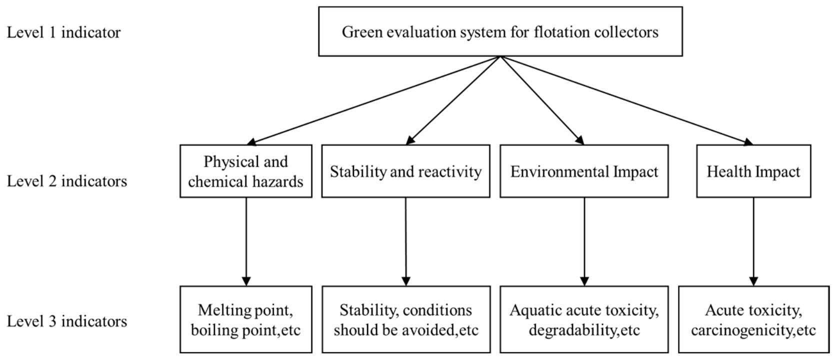

Figure 1. The Green evaluation system of flotation collector.

The evaluation index system consists of three levels of indicators. The primary index is a comprehensive evaluation of the greenness of the flotation collectors; the secondary index consists of the main factors affecting the "greenness" of the collector, including physical and chemical hazards B_1, stability and reactivity B_2, environmental impact B3, and health impact B_4. The four secondary indicators are composed of the main influencing factors of the secondary indicators (i.e., tertiary indicators). The tertiary indicators are the basic indicators of the greenness of the flotation collectors, which are the green factors affecting the greenness of the flotation collector and are expressed by C_i.

2.2. Determination of Index Weight of Flotation Collector Green Evaluation System

The evaluation indicators for the flotation collector green evaluation system are hierarchical, with no correlation between the indicators at different levels. Despite the AHP method being more subjective, it requires less quantitative information and, therefore, has been chosen as the method for determining the indicator weights in the flotation collector green evaluation system [25].

The steps for weight calculation using AHP are as follows:

1. Build a hierarchical model;
2. Constructing the judgment matrix;
3. Calculate the weights;
4. Consistency check.

The weight of the green evaluation index is determined by the analytic hierarchy process, and the weight calculation of each sub-index is shown in Tables S1–S4. The tertiary index weights of the flotation collectors after the consistency check are shown in Table 1.

Table 1. Physical and chemical hazard index weight determination table.

Evaluating Index		Weight	Evaluating Index		Weight
Physical and chemical hazards B1	Melting point C_1	0.0772	Health impact B4	Acute toxicity C_{19}	0.3421
	Boiling point C_2	0.0808		Skin corrosion or irritation C_{20}	0.2353
	Water and oil distribution coefficient C_3	0.0407		Severe eye injury/eye irritation C_{21}	0.1162
	Relative density C_4	0.0309		Characteristic target organ toxicity C_{22}	0.0657
	Molecular weight C_5	0.0216		Carcinogenicity C_{23}	0.0444
	Relative vapor density C_6	0.0267		Reproductive toxicity C_{24}	0.0198
	Upper explosive limit C_7	0.1170		Inhalation hazard C_{25}	0.1765
	Lower explosive limit C_8	0.1473			
	Flash point C_9	0.2626			
	Autoignition temperature C_{10}	0.1952			
Stability and reactivity B2	Stability C_{11}	0.0655	Environmental impact B3	Acute aquatic toxicity C_{15}	0.6528
	Conditions to be avoided C_{12}	0.5731		Aquatic chronic toxicity C_{16}	0.1655
	Hazardous polymerization C_{13}	0.1082		Ozone layer hazard C_{17}	0.1081
	Decomposition product C_{14}	0.2532		Degradability C_{18}	0.0736

2.3. Index Calculation of Flotation Collector Green Evaluation System

2.3.1. Calculation of Three Levels of Indicators for Green Evaluation System of Flotation Collector

For tertiary indicators such as melting point, boiling point, and oil-water distribution coefficient, they have specific numerical values and can be considered quantitative indicators. For quantitative indicators, a mathematical model can be established to calculate the specific score of the indicator. In the green evaluation system of flotation collectors, a normalization function is used to convert the scores of quantitative indicators into a data format [26–28].

The normalization function is a mathematical formula used to compare a series of data, select the appropriate maximum value and the minimum value, then fix the score between 0 and 100; the normalization calculation model is shown in Equation (1).

$$C_i = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (1)$$

Generally speaking, for physical properties, such as melting point C_1, boiling point C_2, water-oil distribution coefficient C_3, relative density C_4, and relative vapor density C_6, the larger the value, the higher the score, which means the greater the value of these properties, the safer and more stable the reagent. For molecular weight C_5, upper explosive limit C_7, lower explosive limit C_8, flash point C_9, and auto-ignition temperature C_{10}, the smaller the value, the higher the score, which means that the greater the value of these properties, the greater the potential hazard.

To quantify the qualitative evaluation indexes objectively and accurately, the evaluation criteria for the assessment of green qualitative indexes of flotation collector were developed. The expert evaluation method was used to score according to the GHS grade classification table and hazard rubric.

To objectively and accurately quantify qualitative evaluation indicators, it is necessary to establish evaluation criteria for the qualitative indicators of green flotation collectors. Since qualitative indicators do not have specific numerical values, it is difficult to accurately convert them into scores. Therefore, the qualitative indicators are evaluated using the expert scoring method. The experts give scores based on the GHS classification table and hazard comments. The final qualitative indicator scoring table is shown below [29–31].

1. Aquatic acute toxicity

From the classification of the aquatic acute toxicity class, it is known that the aquatic acute toxicity class can be divided into three categories, namely, category 1, category 2, and category 3, so the aquatic acute toxicity scoring method is shown in Table 2.

Table 2. Aquatic acute toxicity assessment scale.

Category	Category 1	Category 2	Category 3
Signal word	Warning	Unsignalized word	Unsignalized word
Hazard description	Very toxic to aquatic organisms	Toxic to aquatic organisms	Harmful to aquatic organisms
Fraction	0	65	85

2. Aquatic slow toxicity

From the classification of aquatic slow toxicity level, it can be seen that the aquatic acute toxicity level can be divided into three categories, namely, category 1, category 2, and category 3, so the scoring method of aquatic acute toxicity is shown in Table 3.

Table 3. Aquatic chronic toxicity rating scale.

Category	Category 1	Category 2	Category 3
Signal word	Warning	Unsignalized word	Unsignalized word
Hazard description	Very toxic to aquatic organisms and has a long-term, lasting impact.	Toxic to aquatic organisms and having long-term, lasting effects.	Harmful to aquatic organisms and having long-term, lasting effects.
Fraction	0	65	85

3. Biodegradability

From the biodegradability class classification, it can be seen that the biodegradability class is divided into five categories, and the biodegradability scoring method is shown in Table 4.

Table 4. Biodegradability rating scale.

Category	Category 1	Category 2	Category 3	Category 4	Category 5
Signal word	Hazard	Hazard	Warning	Warning	Warning
Hazard description	No degradation	No degradation	Slow degradation	Rapid degradation (<70%)	Rapid degradation (>70%)
Fraction	0	20	65	75	85

4. Acute toxicity

As can be seen from the classification of acute toxicity levels, the acute toxicity levels can be divided into five categories, and the acute toxicity scoring method is shown in Table 5.

Table 5. Acute toxicity rating scale.

Category	Category 1	Category 2	Category 3	Category 4	Category 5
Signal word	Hazard	Hazard	Hazard	Warning	Warning
Hazard description	Deadly	Deadly	Poisoning	hazardous	May be harmful
Fraction	0	20	65	75	85

5. Skin corrosion or irritation

From the skin corrosion or irritation class division can be seen, the skin corrosion or irritation class can be divided into three categories, namely, category 1A/B/C, category 2, and category 3; skin corrosion or irritation scoring method is shown in Table 6.

Table 6. Skin corrosion or irritation rating scale.

Category	Category 1A	Category 1B	Category 1C	Category 2	Category 3
Signal word	Hazard	Hazard	Hazard	Warning	Warning
Hazard description	Causing severe skin burns and eye injuries	Causing severe skin burns and eye injuries	Causing severe skin burns and eye injuries	Causing skin irritation	Causing mild skin irritation
Fraction	0	0	0	65	85

6. Severe eye injury or eye irritation

From the classification of severe eye injury/eye irritation level, it can be seen that the severe eye injury/eye irritation level can be divided into two categories, and the skin corrosion or irritation scoring method is shown in Table 7.

Table 7. The Scale of severe eye injury or eye irritation.

Category	Category 1	Category 2A	Category 2B
Signal word	Hazard	Warning	Warning
Hazard description	Causing severe eye injury	Causing severe eye irritation	Cause eye irritation
Fraction	0	65	85

7. Specific target organ toxicity

From the classification of specific target organ toxicity classes, it can be seen that the target cell single exposure classes can be divided into three categories, and the target organ toxicity scoring method is shown in Table 8.

Table 8. A Toxicity rating scale for specific target organs.

Category	Category 1A	Category 2	Category 3
Signal word	Hazard	Warning	Warning
Hazard description	Can damage organs	May damage organs	May cause respiratory irritation; or may cause drowsiness, or dizziness
Fraction	0	65	85

8. Carcinogenicity

From the classification of carcinogenicity grade, it can be seen that the carcinogenicity grade can be divided into two categories, and the carcinogenicity scoring method is shown in Table 9.

Table 9. Carcinogenicity rating scale.

Category	Category 1A	Category 1B	Category 2
Signal word	Hazard	Hazard	Warning
Hazard description	May be carcinogenic	May be carcinogenic	Suspected to be carcinogenic
Fraction	0	0	75

9. Germline mutation

From the classification of germ cell mutation classes, it can be seen that germ cell mutation classes can be divided into two categories, and the germ cell mutation scoring method is shown in Table 10.

Table 10. Germline mutation rating scale.

Category	Category 1A	Category 1B	Category 2
Signal word	Hazard	Hazard	Warning
Hazard description	May lead to genetic defects	May lead to genetic defects	Suspicion leads to genetic defects
Fraction	0	0	75

10. Inhalation hazards

From the classification of inhalation hazards, it can be seen that inhalation hazard levels can be divided into two categories, and inhalation hazards are scored in the manner shown in Table 11.

Table 11. Inhalation hazard rating form.

Category	Category 1	Category 2
Signal word	Hazard	Warning
Hazard description	Swallowing and entering the respiratory tract can be fatal	Swallowing and entering the respiratory tract can be harmful
Fraction	0	75

11. Stability

The expressions of stability are indicated by stable and unstable, respectively. The scoring is shown in Table 12.

Table 12. Stability evaluation sheet.

Stability	Fraction
Yes	100
No	0

12. Conditions should be avoided

According to the number of conditions that should be avoided, a certain number of points are deducted for satisfying one condition, and the evaluation based on the linear function is used as an indicator for the classification of decomposition products. The scoring method is shown in Table 13.

Table 13. Conditional scoring tables should be avoided.

Number of Conditions to Avoid	Fraction
0	100
1	80
2	60
3	40
4	20
Be more 5	0

13. Polymerization hazards

Aggregation hazards are indicated by can occur and cannot occur, respectively. The scoring is shown in Table 14.

Table 14. Evaluation scale of polymerization hazard properties.

Can Polymerization Occur	Fraction
Yes	0
No	100

14. Decomposition of products

By decomposition product type, a certain number of points are deducted for one decomposition product. The evaluation based on a linear function is used as an indicator for the classification of decomposition products. The scoring is shown in Table 15.

Table 15. Classification scale of decomposition products.

Specify the Type of Decomposition Products	Fraction
0	100
1	80
2	60
3	40
4	20
5	0

15. Ozone layer hazards

The ozone layer hazard is judged based on whether the substance is a Montreal Protocol substance. The scoring method is shown in Table 16.

Table 16. Ozone Layer Hazard Rating Scale.

Harm the Ozone Layer	Whether the Substance Is Specified in the Montreal Protocol	Signal Word	Hazard Description	Fraction
	Yes	Warning	Destroying ozone in the upper atmosphere	0
	No	Unsignalized word	No	100

2.3.2. Flotation Collector Green Evaluation System II/I Calculation of Primary Indicators

In the green evaluation system of flotation collectors, the calculation of II/I level indicators is obtained by integrating third-level indicators. Due to the significant ambiguity in qualitative indicators and the high independence of each indicator in the process of establishing the index system, the fuzzy comprehensive evaluation method(FCE) is adopted to calculate the II/I level scores of the green evaluation system of flotation collectors [28,32].

In the previous calculation of the collector green index, the index data have been transformed into dimensionless numbers, so the trapezoidal function is chosen to determine the index affiliation. The evaluation set was first established by the assignment method, and the evaluation set V:

$$\mathrm{V} = \{90, 80, 70, 60, 40\} = \{Excellent, Good, Medium, Slightlly\ poor, \mathrm{Poor}\} \tag{2}$$

The corresponding affiliation functions are shown in Figure 2.

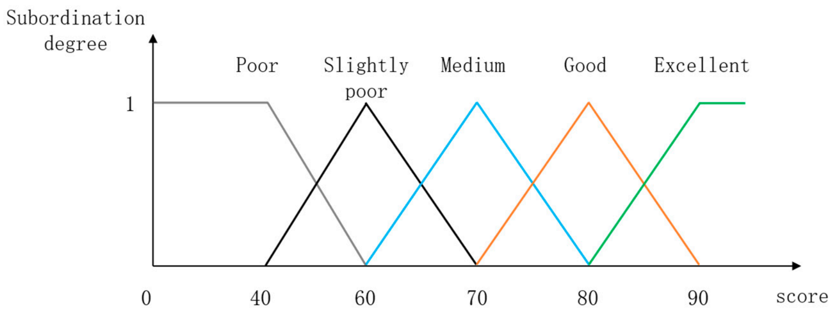

Figure 2. Trapezoidal membership function diagram.

The equation corresponding to the commentary is shown below:

$$A_1 = \begin{cases} 0,\ x \le 80 \\ \frac{x-80}{90-80},\ 80 < x \le 90 \\ 1,\ x > 90 \end{cases} \quad (3)$$

$$A_2 = \begin{cases} 0,\ x \le 70 \\ \frac{x-70}{80-70},\ 70 < x \le 80 \\ \frac{90-x}{90-80},\ 80 < x < 90 \\ 0,\ x \ge 90 \end{cases} \quad (4)$$

$$A_3 = \begin{cases} 0,\ x \le 60 \\ \frac{x-60}{70-60},\ 60 < x \le 70 \\ \frac{80-x}{80-70},\ 70 < x < 80 \\ 0,\ x \ge 80 \end{cases} \quad (5)$$

$$A_4 = \begin{cases} 0,\ x \le 40 \\ \frac{x-40}{80-70},\ 40 < x \le 60 \\ \frac{70-x}{70-60},\ 60 < x < 70 \\ 0,\ x \ge 70 \end{cases} \quad (6)$$

$$A_5 = \begin{cases} 1,\ x \le 40 \\ \frac{60-x}{60-40},\ 40 < x \le 60 \\ 0,\ x \ge 60 \end{cases} \quad (7)$$

In the formula: A_1 is the poor affiliation function; A_2 is the slightly poor affiliation function; A_3 is the medium affiliation function; A_4 is the good affiliation function; and A_5 is the excellent affiliation function.

FCE steps:

Determinant set U:

$$U = \{u_1, u_1, \ldots, u_n\} \quad (8)$$

Determine the rubric set V:

$$V = \{v_1, v_1, \ldots, v_m\} \quad (9)$$

Single-factor evaluation is performed to obtain the single-factor evaluation matrix r_i:

$$r_i = \{r_{i1}, r_{i1}, \ldots, r_{im}\} \quad (10)$$

Construct the integrated judgment matrix R:

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

Integrated judgment weighting:

$$W = \{w_1, w_2, \cdots, w_n\} \tag{12}$$

Calculation of the one-factor vector M using a weighted average type fuzzy operator:

$$M = WR \tag{13}$$

Calculate the evaluation score y based on the weighted average principle:

$$y = MV^T \tag{14}$$

3. Evaluation System of Flotation Effect of Flotation Collector

3.1. Selection of Indicators for the Flotation Effect Evaluation System of the Flotation Collector Based on the Flotation Test

The flotation effect evaluation system indicators based on flotation tests should be selected according to the characteristics of the effect and cost of the flotation collector when it is used [33,34]. The selection of the reagent effect index uses three indicators together, the yield of fine coal C_{26}, the recovery of combustible body $C_{27,}$ and the flotation perfection index C_{28}, to evaluate the flotation effect under different flotation conditions, and the ash is the ash required by the coal preparation plant. The cost is considered as the price of the flotation collectors C_{29} and the amount of the reagent C_{30} in the process of use, and the specific construction steps are shown in Figure 3.

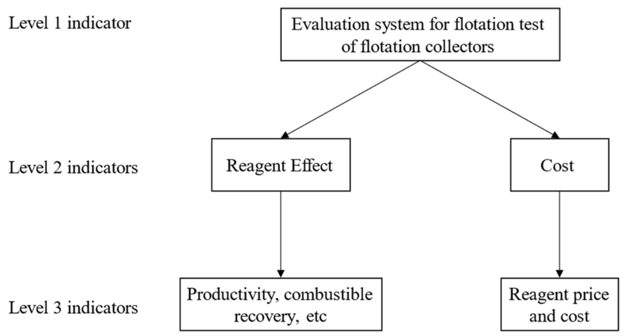

Figure 3. Flotation effect evaluation system of flotation collector based on the flotation test.

3.2. Determination of Index Weights for the Flotation Effect Evaluation System of the Flotation Collector Based on Flotation Tests

The indicators selected for the flotation effect evaluation system based on flotation tests have the characteristics of hierarchical nature, no correlation between indicators at all levels, and less quantitative information required, and AHP was selected as the method for determining the weights of the flotation effect evaluation system based on flotation tests for flotation collectors. The weight of flotation effect evaluation index is determined by analytic hierarchy process, and the weight calculation of each three-level index is shown in Table S5. The weight of the third-level index of flotation collector effect evaluation after consistency test is shown in Table 17.

Table 17. Determination table of the weight of drug effect index.

Evaluation Index		Index Weight
Reagent effect B_5	Clean coal yielding rate C_{26}	0.5396
	Combustible recovery C_{27}	0.2970
	Flotation perfection index C_{28}	0.1634
Reagent cost B_6	Reagent price C_{29} Collector dosage C_{30}	1.0000

3.3. Calculation of Indicators of Flotation Effect Evaluation System of Flotation Collector Based on Flotation Test

3.3.1. Calculation of Three-Stage Indexes of Flotation Effect Evaluation System of Flotation Collector Based on Flotation Test

The test coal sample is quasi-long flame coal with a particle size of −0.5 mm in the Zhungeer mining area of Ordos City. The flotation test was carried out according to GB/T 4757-2013 'Methods for the Batch Flotation Testing of Fine coal'. The ash content of clean coal is less than 15%.

The industrial and elemental analyses of the coal samples are shown in Table S6. The flotation collector list is shown in Table S7.

The ash content of slime flotation concentrate is set below 15%, and a higher yield of concentrate is selected. The results of the coal slurry flotation test are shown in Table S8. The data indicators for the collectors' flotation tests are shown in Table S9.

Based on the flotation test, the three levels of the flotation effect evaluation system of the flotation collector are quantitative indicators, so the method of normalization function is adopted to transform the data of the three levels of indicators of flotation effect into data-score.

The coal concentrate yields C_{26}, combustible recovery C_{27}, and flotation perfection index C_{28} are numerical indicators, all obtained by flotation test, which can be counted directly, and the larger the value, the better. The flotation perfection index is generally lower than 50%, so the maximum value of the flotation perfection index can be taken as 50. The transformation formula of the data-score corresponding to the flotation perfection index is as follows:

$$y = 2x \tag{15}$$

where x refers to the trapping agent flotation perfection index, unit %; and y refers to the collectors' flotation perfection index after the conversion of the fraction.

The cost of chemical B_6 is the product of the chemical dosage C_{30} and the corresponding chemical price C_{29}, which is also a numerical index and can be counted directly, the smaller the value, the better. The normalized formula of collector cost B_6 is as follows:

$$y = 100 - \frac{X - 0}{100 - 0} \times 100 \tag{16}$$

where X refers to the cost of the flotation collector in yuan/ton of dry coal slurry; and y refers to the converted fraction of the flotation collector cost.

Additionally, define that y is less than 0 when the reagent dosage is greater than 100, and define that the fraction is 0 when the cost is greater than 100.

3.3.2. The Evaluation System of the Flotation Effect of the Flotation Collector Based on Flotation Test II/I Index Calculation

The flotation effect evaluation system based on the flotation test is based on the flotation effect of the flotation collector, and the main research indicators are the effect of flotation chemicals (chemical effect and cost). Although the indicators are all quantitative, in the process of establishing the indicator system, we focus on avoiding the duplication of related indicators and the independence of each indicator and select the FCE method to calculate the green evaluation system of the flotation collector second/level score.

In the calculation of index affiliation, the data has been converted into a percentage system. thus, the trapezoidal function was selected to determine the three-stage index affiliation of the flotation test, and the collector flotation test fraction was determined to step by step using the weighted average principle.

4. The Green-Comprehensive Evaluation System of the Flotation Collector

4.1. Index Determination of Comprehensive Evaluation System of Flotation Collector

The primary index of the comprehensive evaluation system of flotation collectors based on the flotation test is the comprehensive evaluation score, and its secondary index is composed of the primary index of flotation collectors green and the primary index of collectors flotation test, so the secondary index of flotation collectors green evaluation system and the secondary index of flotation collectors flotation test are the tertiary indexes of flotation collectors green-comprehensive evaluation system, and the specific construction process of the evaluation system is shown in Figure 4.

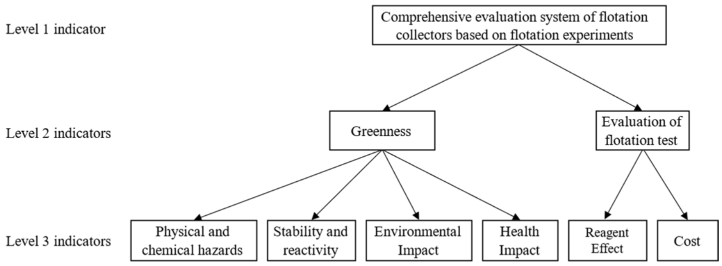

Figure 4. The Comprehensive evaluation system of the flotation collector based on the flotation test.

4.2. Weight Determination of Flotation Collector Comprehensive Evaluation System

AHP was used to calculate the weights of collector indicators at three levels. The secondary index weights are calculated as shown in Table S10. The specific weight calculation results are shown in Table 18.

Table 18. Index table of flotation collector comprehensive evaluation system based on flotation test.

Evaluation Index		Index Weight
Green degree A_1	Physical and chemical hazards B_1	0.0651
	Stability and reactivity B_2	0.0483
	Environmental impact B_3	0.1445
	Health effect B_4	0.2547
Flotation test evaluation system A_2	Reagent effect B_5	0.3854
	Reagent Cost B_6	0.1022

4.3. Comprehensive Evaluation Calculation of Flotation Collector

The main research index of the comprehensive evaluation system of flotation collector is the evaluation of the whole process of flotation collector use, and its evaluation index includes the greenness and flotation effect. The FCE method is selected to calculate the score of the green-comprehensive evaluation system of the flotation collector.

5. Example Analysis of Comprehensive Evaluation of Flotation Collectors

According to the data collected by PubChem [35–37], the data-score transformation of the collector green index data was performed using the qualitative and quantitative index calculation models discussed in the previous section, and the final score results are shown in Table 19. The collector green index data are shown in Table S11.

Table 19. Green index score table of collector.

Green Index	Dodecane	Dodecyl Aldehyde	Methyl Laurate	N-Octane	1-Octanol	2-Octanone	Valeraldehyde
C_1	63.82	88.41	70.55	42.36	61.14	60.91	26.59
C_2	70.00	58.93	88.21	37.86	62.50	55.00	29.64
C_3	86.15	69.06	75.54	72.00	38.46	28.77	12.46
C_4	49.74	67.00	73.00	40.60	65.80	64.00	62.20
C_5	55.06	50.23	39.88	74.40	68.89	69.58	84.09
C_6	18.75	57.50	79.46	2.68	73.21	71.43	46.43
C_7	73.33	56.67	55.83	70.83	87.50	87.50	60.00
C_8	5.00	25.00	40.00	15.00	15.00	35.00	80.00

Table 19. *Cont.*

Green Index	Dodecane	Dodecyl Aldehyde	Methyl Laurate	N-Octane	1-Octanol	2-Octanone	Valeraldehyde
C_9	55.33	67.33	89.33	8.67	54.00	34.67	8.00
C_{10}	12.69	11.54	49.23	13.85	31.92	23.46	20.00
C_{11}	100.00	100.00	100.00	100.00	100.00	100.00	100.00
C_{12}	80.00	80.00	40.00	80.00	40.00	40.00	20.00
C_{13}	100.00	100.00	100.00	100.00	100.00	100.00	100.00
C_{14}	60.00	60.00	60.00	60.00	60.00	60.00	60.00
C_{15}	85.00	65.00	0.00	0.00	0.00	85.00	85.00
C_{16}	85.00	65.00	65.00	0.00	0.00	85.00	85.00
C_{17}	100.00	100.00	100.00	100.00	100.00	100.00	100.00
C_{18}	0.00	65.00	75.00	0.00	65.00	0.00	65.00
C_{19}	85.00	85.00	75.00	75.00	75.00	75.00	85.00
C_{20}	65.00	65.00	65.00	65.00	85.00	65.00	65.00
C_{21}	85.00	65.00	85.00	65.00	65.00	65.00	65.00
C_{22}	65.00	65.00	85.00	85.00	0.00	85.00	85.00
C_{23}	0.00	75.00	75.00	0.00	75.00	75.00	75.00
C_{24}	75.00	75.00	75.00	75.00	75.00	75.00	75.00
C_{25}	0.00	75.00	75.00	0.00	75.00	75.00	75.00

The data-fraction transformation of the collector flotation effect index was performed. The data-score conversion of the collector flotation effect index is shown in Table 20.

Table 20. Collector flotation test index score table.

Effect Index	Dodecane	Dodecyl Aldehyde	Methyl Laurate	N-Octane	1-Octanol	2-Octanone	Valeraldehyde
C_{26}	45.41	57.05	54.26	32.29	36.48	32.05	38.24
C_{27}	53.30	66.55	63.68	38.25	42.83	37.77	44.79
C_{28}	53.76	65.46	63.96	38.10	43.60	38.76	43.70
C_{29}*C_{30}	60.00	50.00	82.00	90.00	80.00	70.00	40.00

The results of green evaluation and flotation effect evaluation of flotation collector using FCE method are shown in Tables 21 and 22.

Table 21. Green comprehensive evaluation table of flotation collector.

Collector	A_1	B_1	B_2	B_3	B_4
Dodecane	71.56	65.69	72.67	82.32	68.84
Dodecyl aldehyde	70.45	57.10	76.67	67.70	74.25
Methyl laurate	74.19	66.38	53.75	84.06	74.47
N-octane	57.85	45.85	76.67	45.41	64.41
1-octanol	62.07	54.94	53.75	47.25	73.89
2-octanone	70.52	50.60	53.75	82.23	72.14
Valeraldehyde	72.66	50.04	53.75	84.07	75.56

Table 22. Comprehensive score table of collector flotation test evaluation system.

Collector	A_2	B_5	B_6
Dodecane	53.14	49.71	60.00
Dodecyl aldehyde	57.50	61.25	50.00
Methyl laurate	66.43	58.64	82.00
N-octane	56.67	40.00	90.00
1-octanol	54.28	41.43	80.00
2-octanone	50.00	40.00	70.00
Valeraldehyde	41.35	42.03	40.00

B_1, B_2, B_3, B_4, B_5, and B_6 were synthesized by FCE method, and the results are shown in Table 23. From Table 23 and it can be seen that in the comprehensive evaluation system of flotation collector t based on the flotation test, methyl laurate has the highest comprehensive score with its score of 69.01, n-octane has the lowest comprehensive score with its score of 54.27, and the rest of the comprehensive scores of collectors are between methyl do decanoate and n-octane.

Table 23. Comprehensive evaluation score table of flotation collector based on flotation test.

Collector Name	Overall Score
Dodecane	61.97
Dodecyl aldehyde	64.83
Methyl laurate	69.01
N-octane	54.27
1-octanol	55.96
2-octanone	58.72
Valeraldehyde	57.53

From Figure 5 flotation test-based flotation collector comprehensive evaluation system in the secondary index radar chart can be seen, for example, dodecane, the dodecane secondary index radar chart, the effect of the reagent and cost performance is poor, so the comparability between the secondary index radar chart, there can be differences in comparing the secondary index, which in turn can verify the flotation test-based flotation collector comprehensive evaluation system established by the reasonableness, intuitive, and scientific. The effectiveness of the evaluation system can be verified by comparing the radar plots between different reagents, and the radar plots between different reagents can be compared to evaluate different flotation collectors.

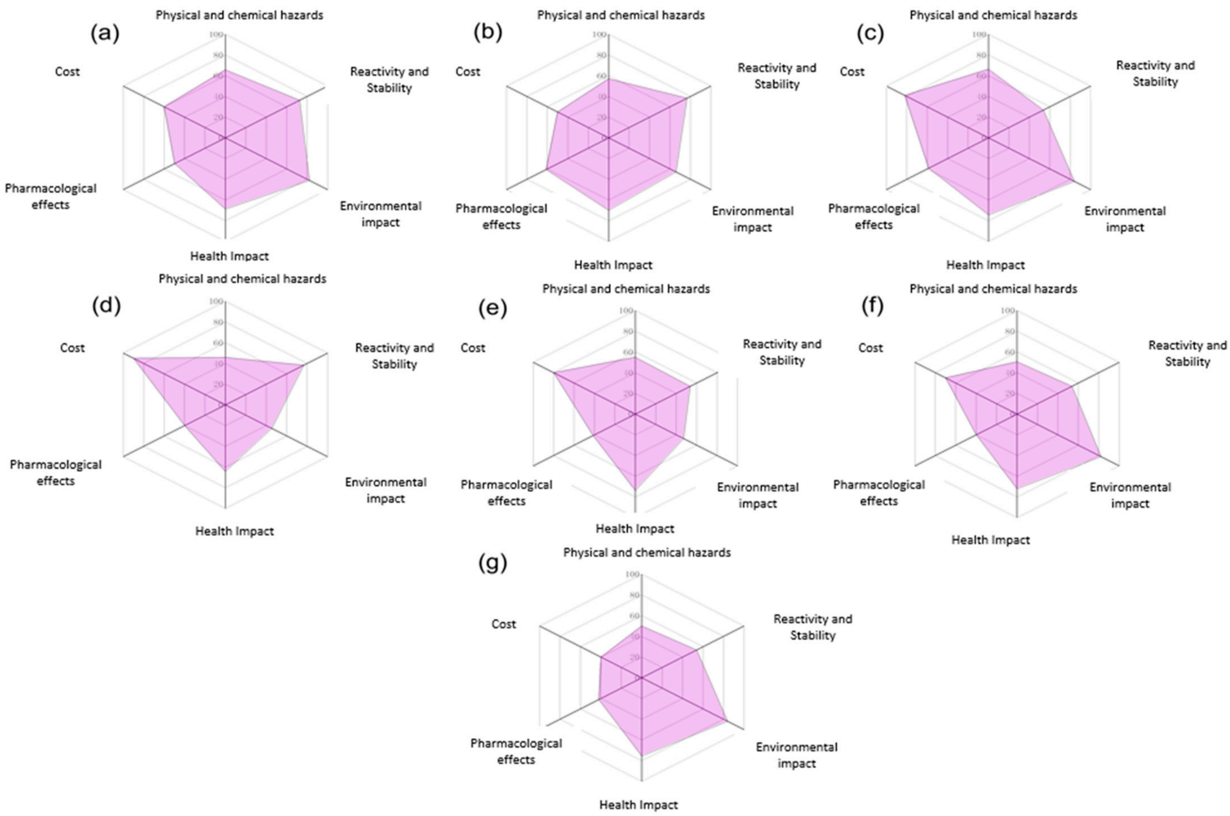

Figure 5. Comprehensive evaluation system of collectors based on flotation test radar data: (**a**) dodecane, (**b**) dodecyl aldehyde, (**c**) methyl laurate, (**d**) n-octane, (**e**) 1-octanol, (**f**) 2-octanone, and (**g**) Valeraldehyde.

Previously, the evaluation of the flotation of the collector was carried out by flotation effect only, without taking into account the physical and chemical hazards of the collector, health hazards, and other factors. In this work, the inherent nature (green color) of the flotation collector is combined with the flotation effect to provide a comprehensive evaluation and selection method of the flotation collector, which makes the evaluation of the flotation collector more reasonable and scientific.

6. Conclusions

1. According to the use of flotation collectors in coal processing plants, the green evaluation system of flotation collectors was constructed by using the analytical method, and the basis for selecting green indicators of flotation collectors was established according to chemical safety technical instructions and Globally Harmonized System of Classification and Labeling of Chemicals (GHS).
2. The flotation effect evaluation system based on the flotation test is constructed by using the analytical method, and the indicators are determined by the method of flotation test commonly used in the laboratory: secondary indicators, i.e., the effect and cost of chemicals, and tertiary indicators under the secondary indicators: the yield of fine coal, the recovery of combustible body and the price of chemicals, etc., forming the evaluation system of "1-2-5".
3. The comprehensive evaluation model of the flotation collector based on the flotation test has constructed a four-level evaluation index system of "1-2-6-30" from two dimensions: green and flotation test.
4. The reasonableness, intuitiveness, and scientificity of the establishment of the comprehensive evaluation system can be verified by the difference between radar plots of secondary and tertiary indicators. The effectiveness of the evaluation system can be verified by the comparison of radar plots between different reagents, and the comparison of radar plots between different reagents can be used to evaluate different collectors.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/pr11051563/s1, Table S1: Physical and chemical hazard index weight determination table; Table S2: Stability and reactivity index weight determination table; Table S3: Table for determining the weight of environmental impact indicators; Table S4: Weight determination table of health impact indicators; Table S5: Determination table of weight of drug effect index; Table S6: Industrial analysis and elemental analysis of long flame coal; Table S7: Collector list; Table S8: Experimental results of coal slurry flotation with different collectors; Table S9: Collector flotation test data index table; Table S10: Weight determination table of three index of flotation collector comprehensive evaluation system based on flotation test; Table S11: Green data index of collector.

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